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Gas permeability and retention study on Ämmässuo temporary landfill cover structures made with Municipal Solid Waste Incineration Bottom Ash

Master's thesis submitted for examination for the Master of Engineering Degree

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Abstract of master's thesis

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Abstract

This thesis was focused on the gas permeability and retention study of the temporary landfill test cover structures made with Municipal Solid Waste Incineration Bottom Ash (MSWI BA). This study was done for Helsinki Region Environmental Services Authority to incorporate MSWI BA in the impermeable layer of the landfill cover structure. Accordingly, gas permeability studies were done in the Ämmässuo landfill on two different landfill test cover structures made with MSWI BA. Literature review was done for acquiring the knowledge on landfill cover construction, gas flow mechanism and the factors affecting the gas emission through the landfill cover structures. Impermeable layer of one of the test structures was made with 0-5mm MSWI BA and the other structures was made with 0-2mm MSWI BA and 3% polymer modified sodium bentonite. There was a considerable difference in the measured gas emission above the impermeable layer between these two test structures. This research study also explored the factors affecting the gas emissions through the impermeable layer of the landfill test structures. In addition to the gas permeability study of the two different landfill test cover structures, an experimental study was done on the MSWI BA-clay mixture to use it as an improved construction material for the impermeable layer of the landfill cover structure.

The analysis on the gas measurements of the two test cover structures revealed that the test structure which was made with MSWI BA (0-2mm) and 3% polymer modified sodium bentonite was more effective in reducing the landfill gas emission than the other one. Experimental study results on MSWI BA-clay mixtures exhibited that the requirements of impermeable layer could not be completely satisfied with mixtures used for the tests. Outcome of this thesis aided Ämmässuo landfill in constructing a new temporary test landfill cover structure in autumn 2018.

Keywords Landfill, Temporary cover structures, gas permeability, MSWI Bottom ash

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Diplomityön tiivistelmä

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Tiivistelmä

Tämän työn tavoitteena oli tutkia jätteenpolton kuonasta tehtyjen väliaikaisten pintarakenteiden kaasunläpäisevyyttä ja -pidätyskykyä. Tämä tutkimus tehtiin Helsingin Seudun Ympäristöpalvelu Oy:lle edistämään jätteenpolton kuonan hyötykäyttöä kaatopaikkojen pintarakenteen tiivistyskerroksessa. Työn ydinosana olivat kahdesta aiemmin rakennetusta koerakenteesta tehdyt kaasunläpäisevyysmittaukset Ämmässuolla.

Kirjallisuuskatsaus kattoi kaatopaikan pintarakenteet, kaasun kulkutusmekanismit ja pintarakenteen kaasunläpäisevyyteen vaikuttavista tekijöistä. Ensimmäisen koerakenteen tiivistyskerros oli rakennettu jätteenpolton kuonalla, jonka rakeisuus vaihteli välillä 0-5mm. Toisen rakenteen tiivistyskerros oli rakennettu polymeerillä modifioidulla natriumbentoniittiseoksella, jonka runkoaineena oli 0-2 kuona. Mittausten tavoitteena oli selvittää ne tekijät, jotka vaikuttavat kaasunläpäisevyyteen. Näiden kahden koerakenteen kaasumittauksista tehdyn analyysin perusteella havaittiin, että polymeerimodifioidulla natriumbentoniitiseoksella tehdyn koerakenteen kaasuntiiviys oli selkeästi parempi kuin pelkän kuonarakenteen. Siksi työhön lisättiin esiselvitys parannetun savi-kuonaseoksen ominaisuuksista laboratoriossa. Työn koetuloksia hyödynnettiin syksyllä 2018 rakennetussa uudessa Ämmässuon väliaikaisessa pintarakenteessa.

Avainsanat Kaatopaikka, väliaikainen pintarakenne, jätteenpoltonkuona

Preface

This thesis work was done for Helsingin Seudun Ympäristöpalvelu Oy, thereby aiding Ämmässuo landfill in utilising municipal solid waste incineration bottom ash for landfill cover construction. I am grateful to HSY for the funding and giving me an opportunity to take part in this interesting study. This study enabled me in exploring more on landfill construction.

I am thanking my thesis supervisor Professor Leena Korkiala Tanttu, thesis advisor Heikki Hämäläinen and Professor Minna Leppänen for the support and valuable comments during this thesis work. Many thanks to staff of Ämmässuo landfill, especially Tapio Jantunen and Jyrki Saari for supporting me in field measurements. I am also thanking Matti Ristimäki for the assistance and guidance given during the laboratory tests.

I dedicate this thesis to my husband and our lovely girls. Without your support, I could not able to fulfil this dream. I also would like to thank my parents, relatives and friends for supporting me throughout my Master's programme by understanding my hectic schedule during the study period.

Espoo 03.12.2018

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Abbreviations

ppm	parts per million
%	percentage
%v/v	Percentage by volume
CaO	Calcium Oxide
ATSDR	Agency for Toxic Substances and Disease Registry
$Ca(OH)_2$	Calcium hydroxide
CFI	Carbon Farming Initiative
CH_4	methane
CO_2	carbon dioxide
DP-IR	Detecto Pak-Infrared
epaIreland	Environment protection agency Ireland
Ea E&W	Environment agency, England and Wales
epaVictoria	Environment protection authority Victoria
EU	The council of the European Union
GCL	Gas Collection Layer
ha	Hectare
HSY	Helsingin seudun ympäristöpalvelut
H_2	Hydrogen
H_2S	Hydrogen sulphide
LCL	Lower Check Layer
LEL	Lower Explosive Limit
LLDPE	Linear Low Density Polyethylene
milj.nm^3	Million normal cubic meter
MSWI BA	Municipal Solid Waste Incineration Bottom Ash
N_2	Nitrogen
O_2	Oxygen
PEL	permissible exposure limit
RTS	Rakennustietosäätiö
STEL	short-term-exposure limit
SYKE	Suomen Ympäristökeskus
UCL	Upper Check Layer
UEL	Upper Explosive Limit
USACE	US Army corps of engineers
VNa	Valtioneuvoston asetus

Symbols

A	[m^2]	Area of flux box
Cu	[kPa]	Undrained shear strength
K	[m/s]	Coefficient of water permeability
w	[%]	water content
λ	[W/mK]	Thermal conductivity
dc/dt	[$mg/m^3/s$]	Rate of change of gas concentration in the chamber with time
V	[m^3]	Volume of flux box
Q	[$mg/m^2/s$]	Flux density of the gas/surface emission rate

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1 Introduction

According to recent studies, emission of greenhouse gases such as carbon dioxide, methane, nitrous oxide and halogenated compounds can have a major role in the global warming. Greenhouse gases can accumulate heat in the atmosphere by absorbing the infrared radiation, thereby enhancing the global warming. (Kweku et. al., 2018.) Greenhouse gases can be generated from various sources such as transportation sector, electricity production, agricultural farms, landfills, etc. Landfill is the waste disposal site for the deposit of waste. Thus, gases generated from the landfill can have a higher concentration of greenhouse gases such as methane and carbon dioxide (Ea E&W, 2004). In addition to the global warming effect, gases emitted from the landfill can create several other adverse effects on the environment and human health. According to European Union and Finnish legislation, for controlling gas emission from the landfills, a cover structure and a gas collection system had to be constructed at the landfills. A cover structure must be constructed over the landfills, after closure of hazardous and non-hazardous landfills. (EU, 1999.; VNa 331/2013.) Thus, the aim is to reduce the water infiltration into the waste and the gas emission from the waste. However, according to the recent studies, landfill gases cannot be completely collected with a gas collection system. When a certain gas pressure is reached, part of the generated landfill gases can emit to the atmosphere through the landfill cover structure (Zhongkui, 2016). Thus, the permeability of the landfill cover structure affects highly the gas emission through the structure. Accordingly, this research was focused on the gas permeability performance of the landfill cover structures.

Landfill cover structure is a multi-layered system, construct usually with a natural mineral material such as clay, sand, gravel, etc. Thus, a large quantity of natural soil is required for landfill cover construction. Consequently, excavation of these natural mineral materials can put strain on environment significantly. However, as an alternative solution, Municipal Solid Waste Incineration Bottom Ash (MSWI BA) can be used as a construction material for the landfill cover structure due to its good civil engineering properties and availability. MSWI BA is a by-product generated from municipal solid waste incineration and it is considered as a non-hazardous secondary construction material (Sormunen, 2017). Furthermore, in Finland, according to new waste act from 1.1.2016, organic waste with organic carbon greater than 10% can no longer been disposed in the landfills. Thus, instead of landfilling, organic wastes are burned in incineration plants (HSY 2017). Accordingly, annually around 300 000 tonnes of bottom ash are generated by incineration of the municipal solid waste in Finland (Suomen Eritysjäte Oy, 2018). Some portion of these generated bottom ash can be used in making landfill cover structures.

Even though many studies have been done for incorporating bottom ash in the landfill cover construction, only a very few studies are done on the gas permeability of the landfill cover structure. Gas permeability of the landfill cover structure can highly influence the emission of the landfill gases. Landfill cover structure with low gas permeability have low landfill gas emission. Consequently, this research study aimed at the gas permeability performance of the landfill cover made with MSWI BA and explored the factors affecting gas emission through the impermeable layer of the landfill cover. This research study was done in Ämmässuo landfill for Helsinki Region Environmental Services Authority (HSY) during the period April - September 2018. Outcome of this research study can benefit HSY while

constructing the new test cover structure, that is planned to be constructed during autumn 2018.

Gas permeability of the landfill cover structure was studied in Ämmässuo landfill by analysing landfill gas measurements taken from two test structures made with MSWI BA. First test structure was constructed in 2015 with MSWI BA and polymer modified bentonite. Second test structure was constructed in 2017 mainly with MSWI BA. During the four months period, gas measurements were taken from different layers of the test structures, through observation pipes and flux boxes by using the gas analyser. A literature review was conducted to acquire the knowledge about gas generation, gas emission, gas flow mechanism through landfill cover structures and properties of the MSWI bottom ash.

During the research, an experimental study was also done on MSWI BA-clay mixture as a construction material for the impermeable layer of the landfill cover structure. Constructability of the MSWI BA-clay mixture had been tested and the geotechnical tests were done for understanding the suitability in the landfill cover structure construction. Based on the outcome from this experimental study, a part of the new landfill test cover structure was built using the MSWI BA-clay mixture during autumn 2018.

During this research, it was only possible to study gas permeability performance of two kinds of landfill cover structures made with MSWI BA. If there was an opportunity to study more landfill cover structures, it could have helped in establishing even more reliable conclusions on the impermeable layer characteristics and its gas permeability.

2 Landfill cover structures and gas emission control

Landfills are carefully designed structures for disposing waste. Thus, landfills are constructed inside or top of the ground in order to isolate the dumped waste from the surrounding environment there by preventing the surrounding environment from the disposed waste. Depending on the type of the disposed waste, landfills are classified into three such as landfill for hazard waste, landfill for non-hazard waste and landfill for inert waste. Landfill structures mainly consist of a bottom liner system and a cover structure as described in the Figure 2.1. (RTS, 2018.)

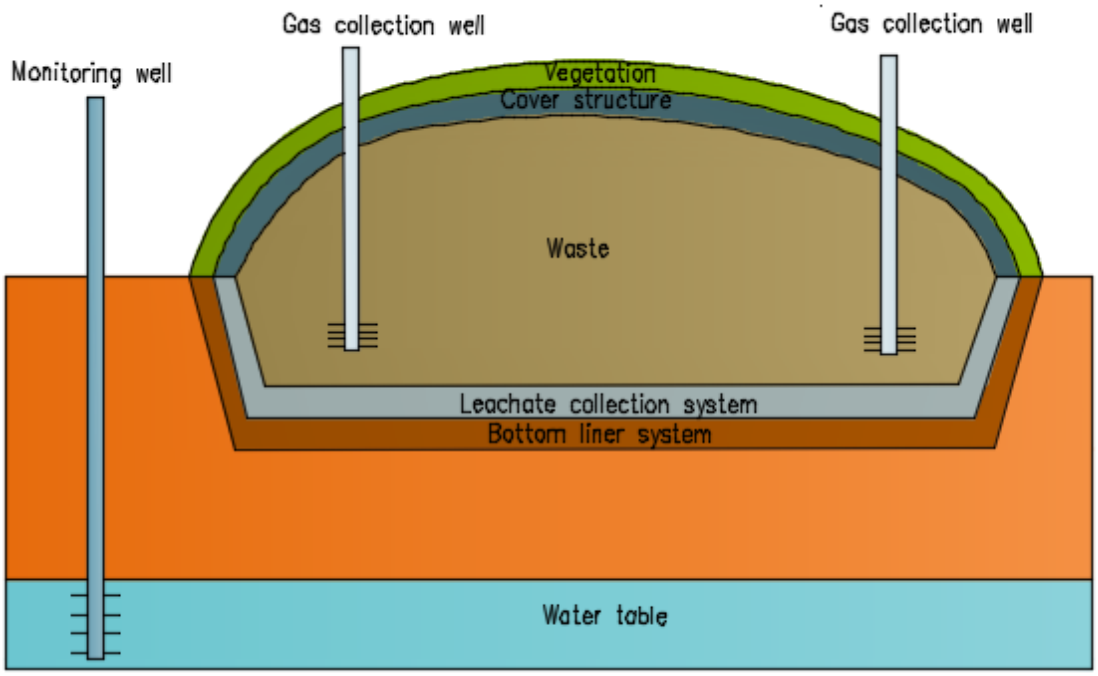


Figure 2.1 Simplified cross section of landfill (Figure: Amended from Barlaz, 2016)

As illustrated in the Figure 2.1, landfill structure has a bottom liner situated below the disposed waste. The bottom liner act as a barrier between the disposed waste and the soil beneath it, thereby preventing the contact between the disposed waste and the soil. Thus, the bottom liner also prevents the contamination of the underground water from the disposed waste. Furthermore, degradation of the disposed waste inside the landfill generates large quantity of gases. Therefore, in order to isolate the disposed waste from the outside environment, a cover structure is constructed over the disposed waste. Cover structure not only prevents the gas migration into the atmosphere but also restricts the infiltration of the rain water into the disposed waste. (RTS, 2018.)

This research study is focused on the landfill cover structure and reducing the gas emission through the cover structure from the landfill. Thus, the landfill gas generation, gas emission, gas control measures and gas transport mechanisms will be discussed in the sections 2.1 to 2.6.

2.1 Landfill gas generation and composition

Gases from the landfills are generated by the degradation of the deposited waste. Degradation of the waste in the landfills happens through the bacterial decomposition, volatilisation and chemical reactions. During bacterial decomposition, organic solid waste is degraded by bacteria present in the waste and soil. During volatilization process, some part of the liquid/solid waste is converted into vapour. Some part of the deposited waste can degrade through the chemical reaction between the mixed waste materials. Usually, a landfill site accepts wastes for 20 to 30 years. Thus, during the long period of the waste disposal, within the landfill, properties of the deposited wastes may vary from one place to another due to the difference in the aging of the deposited waste. Therefore, throughout the landfill life, gas generation rate and composition may vary significantly within the landfill locations. Gas generation rate and composition depends upon several factors such as physical dimensions of the landfill site, type of the waste deposited, age of the waste, moisture content, pH, temperature, density of the waste, compaction, application of the cover, etc. Figure 2.2 illustrates the changes in the composition of the landfill gas generation with time. (USACE, 2008.)

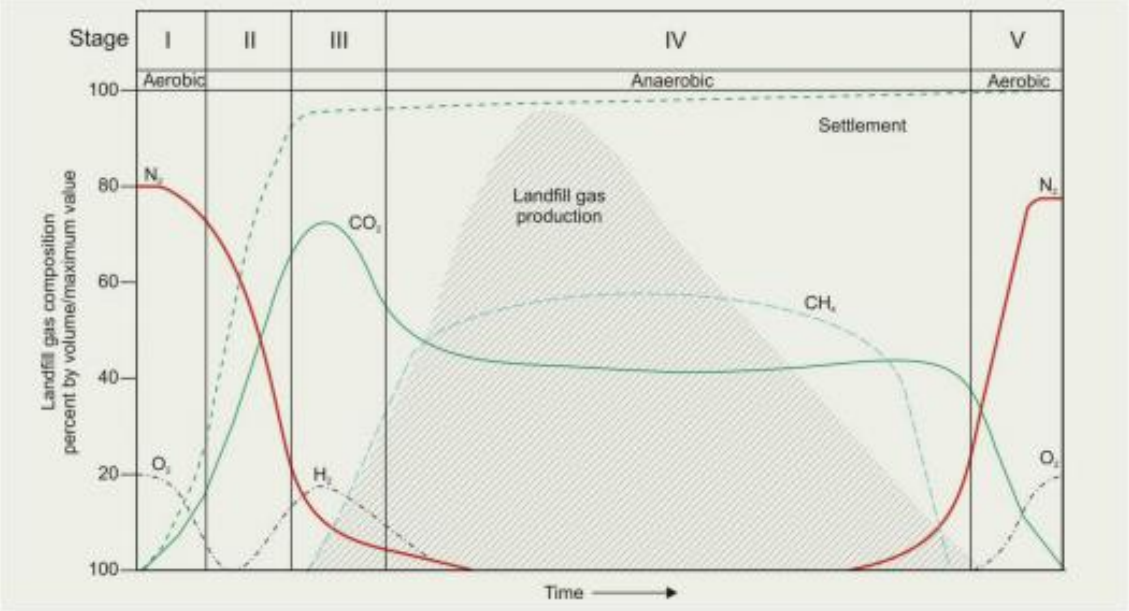


Figure 2.2 Changes in the production and composition of landfill gas over time (Figure: EPA Ireland, 1997)

As described in the Figure 2.2, there are mainly four phases of degradation, which takes place in the landfills with time. In the phase I, aerobic bacteria present in the soil and waste, decompose the organic waste by consuming the oxygen. The main by-product in the first phase is carbon dioxide (CO_2). Nitrogen (N_2) content is high in this stage and will get reduced in the successive stages. Phase I continues until the amount of oxygen diminishes. This phase may last for days or months, depending upon the available amount of oxygen (O_2). In the Phase II degradation, compound created in Phase I transformed into acetic acid, lactic acid, formic acid and alcohols such as methanol and ethanol by the action of anaerobic bacteria. Generated acids thus mix with the moisture in the landfills and generates nitrogen and phosphorous. The gaseous by-products in this phase are carbon dioxide (CO_2) and hydrogen (H_2). However, in the phase II, if the amount of oxygen increases in some way, degradation

will then change into phase I stage. In the phase III, acetate and organic acids will be created by anaerobic bacteria consuming the organic acids that are produced in the second phase. Thus, this environment becomes suitable for methane-producing bacteria (methanogens) to establish. Consequently, by consuming the hydrogen (H_2), these methanogens can potentially degrade the volatile acids and the acetic acid. Resulting in the generation of methane (CH_4) and carbon dioxide (CO_2). In the phase IV, gas composition and the gas generation attain a steady state. In this stage, landfill gas typically consists of 45 to 60 percent of CH_4, 40 to 60 percent CO_2 and 2 to 9 percent other gases, such as sulphide, etc. (ATSDR, 2001.) Table 2.1 shows the concentration of typical landfill gas components by volume.

Table 2.1 Typical landfill gas components by volume (Table: ATSDR, 2001)

Bulk landfill gas	**Typical value (%v/v)**
Methane	45 - 60
Carbon dioxide	40 - 60
Nitrogen	2 - 5
Oxygen	0.1 - 1
Ammonia	0.1 - 1
NMOCs (Non-methane organic compounds)	0.01 – 0.6
Sulphides	0 - 1
Hydrogen	0.05
Carbon monoxide	1.8

Typically, phase IV stage lasts for about twenty years. However, emission of the gases will be continued for about fifty years or more after the wastes are disposed in the landfill. In certain situations, when the landfill site gets interrupted, then the gas generation can accelerate again. This happens when the moisture content and available oxygen increase in the landfill waste. This is considered as phase V. Phase V stage depends on the changes in the ground water table and/or the efficiency of the cover structures. (USACE, 2008.)

Density of the landfill gas can be changed, and it depends up on the gas composition. A mixture of 60 per cent CH_4 and 40 per cent CO_2 is the typical concentration of landfill gas. And the density of the composition is typically 1.19kg/m^3 which is slightly lighter than the air. Viscosity of such gas mixture is also smaller than air and it is typically 1.17×10^{-5} Pa s. (EA E&W, 2004.) Table 2.2 shows typical values of density and viscosity of gases at 0˚C and at atmospheric pressure.

Table 2.2 Typical values of density and viscosity of gases at 0˚C and at atmospheric pressure (Table: USACE, 2008)

Gas	Density(kg/m^3)	Viscosity (Pa s)
Air	1.29	1.71 x 10^{-5}
Methane	0.72	1.03 x 10^{-5}
Carbon Dioxide	1.9	1.39 x 10^{-5}
50% CH_4 + 50% CO_2	1.35	1.21 x 10^{-5}
60% CH_4 + 40% CO_2	1.19	1.17 x 10^{-5}

2.2 Adverse effects of landfill gas emission

As discussed in section 2.1, landfill emits various kind of gases. Most of the landfill emitted gases have adverse effects on humans and the environment. Table 2.3 describes how the landfill gas components and its concentration are adversely affecting the atmosphere.

Table 2.3 Landfill gas characteristics (Table: USACE, 2008)

Constituent	Relative specific gravity	Concentration in landfill gas	Notes
Air	1	NA	Forms explosive mixture with methane
Methane	0.554	40 - 70%	Explosive; LEL 5% in air; UEL 15% in air
Carbon dioxide	1.529	30 - 60%	Forms weak acid; Asphyxiant
Hydrogen sulphide	1.19	800ppm	Forms strong acid Toxic: PEL=10 STEL=15
water vapour	0.62	100% saturated	Forms acids with hydrogen sulphide and carbon dioxide
Benzene	2.8	30ppm	Flammable Toxic: PEL 1.0ppm STEL 5 ppm
Toluene	3.1	300ppm	Toxic: PEL 100 ppm STEL 150ppm
Organic acids	GT 2	Traces	Odorous
Organosulphur compounds	GT1.5	50ppm	Odorous

LEL=lower explosive limit; UEL=upper explosive limit; STEL=short-term-exposure limit; PEL=permissible exposure limit

As described in the Table 2.3, various constituents that are present in the landfill gases can dissolve in aqueous media and thus can contaminate the water source. For instance, methane gas is slightly soluble in the aqueous media. On the other hand, solubility of CO_2 is high in the aqueous media. Some of the constituents of landfill gas can create toxic effects if their concentrations are high enough. For instance, presence of higher concentration benzene and toluene can create toxic effect. (EA E&W, 2004.)

Methane (CH_4) a colourless and odourless gas is not considered as toxic to plants or other organisms. But due to its flammable and explosive properties, CH_4 gas can be extremely harmful to the people and properties. CH_4 gas can generate energy of 35.9 MJ/m^3, when it is burned. When CH_4 gas concentration is in between 4.4 % and 16.5 % by volume at 20˚C and 1 atmosphere pressure, it can form explosive mixtures with air. This may potentially endanger the properties and lives of workers in landfills and residents living near landfill sites. It is very likely that landfill gas can have the traces of other inflammable gases such as hydrogen gas and hydrogen sulphide. Flammable limits of H2 gas is 4–75% and hydrogen sulphide gas is 4–44%. (EA E&W, 2004.)

Even though, lower concentrations of methane in the air does not directly affect the human health, but a very high concentration of methane in the air can displace oxygen and makes risk of asphyxiation. When the atmospheric oxygen reduced below 10%, it can potentially result in asphyxia. Dizziness, headache, palpitations, visual disturbance, confusion etc are the symptoms often happens with the asphyxiation. Long exposure below 16% oxygen can even lead to consciousness, and in extreme instance resulting in death. (EA E&W, 2004.) However, methane from the landfill gas can be used for producing energy, which is an economical collection advantage of the landfill gas. (EA E&W, 2004.; Fischer et al., 1999.)

As described the Table 2.3 another constituent of the landfill gas is hydrogen sulphide. Hydrogen sulphide in landfill gas is toxic even at a very low concentration. (EA E&W, 2004.) It is a highly odorous gas and odour threshold of hydrogen sulphide is 0.008ppm only. The explosive range of hydrogen sulphide in air is 4.3% - 46%. According to world health organisation, the average concentration of hydrogen sulphide in the outside air should be less than 0.005 ppm/30 minute. At work places, the concentration should be less than 5 ppm (7 mg/m^3) /8 h. (Työterveyslaitos, 2018.)

Landfill gas often constitute 30-60% of carbon dioxide. Higher concentration of CO_2 in the atmosphere can cause phycological issues to humans. The below Table 2.4 highlight the physiological effects of exposure to carbon dioxide. (EA E&W, 2004.)

Table 2.4 Physiological effects from respiration of carbon dioxide (Table: EA E&W, 2004)

Concentration of carbon dioxide (%)	Physiological effects
0.03	None, normal atmospheric concentration
0.5	Slightly deeper breathing
2.0	Lung ventilation increased by 50 percent
3.0	Lung ventilation doubled
5 - 10	three-fold increase in rate of respiration. Rapid exhaustion and headaches
10 - 15	Intolerable panting. Severe headaches, collapse
25	Death

Furthermore, trace compounds present in the landfill gas makes malodours in the landfilling operations. Commonly reported odorants in the landfill gases are hydrogen sulphide, organo-

sulphur compounds, carboxylic acids, carbon disulphide, etc. The presence of trace compounds as well as the odour in the landfill gas emissions can also have adverse effects on human health. Under some atmospheric conditions, the generated malodours may travel to kilometres away from the landfill site. Thus, the persistent malodour can affect the quality of life in the neighbouring area. Some of the landfill gases components and their derivatives can be potential for corrosion. Consequently, corrosion accelerates wear on plant and equipment especially affecting the performance of the gas control measures in the landfill area. (EA E&W, 2004.)

As explained above, presence of greenhouse gases such as CH_4, CO_2 and various kind of halocarbons in the landfill gas can potentially create global warming. Worldwide, landfills produce 20 to 60 Tera-grams of methane per year. (EA E&W, 2004.; Robinson et al., 2003.) Global warming potential (GWP) is a comparative measure showing the amount of heat that a greenhouse gas entraps in the atmosphere with respect to the reference gas. This is calculated for a specific interval of time. CO_2, which has 100-year GWP of 1 is considered as the reference gas. For a 100-year period, GWP of CH_4 is 25 times higher than CO_2. (Eurostat, 2018.)

2.3 Landfill gas emission sources

As described in section 2.2, numerous kinds of pollutants from landfill gas can be potentially emitted to the atmosphere due to the operations in the landfills. This section explains the sources of landfill gas emission. Various sources can generate gas emissions in the landfill. Figure 2.3 is a schematic representation of the different sources of gas emission from a completed landfill.

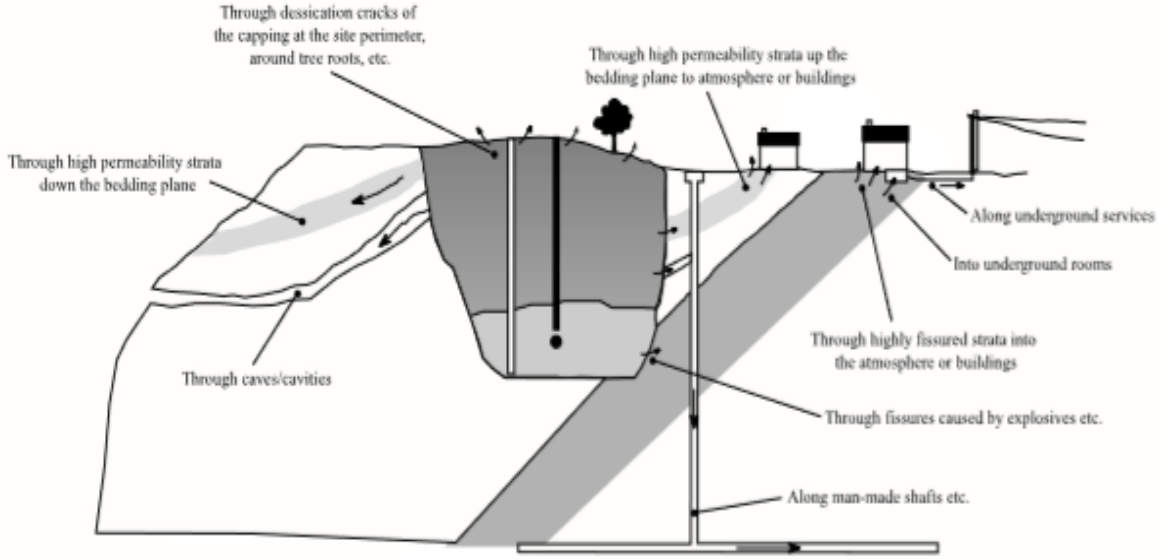


Figure 2.3 Different sources of gas emission from a completed landfill (Figure: epaIreland, 1997*)*

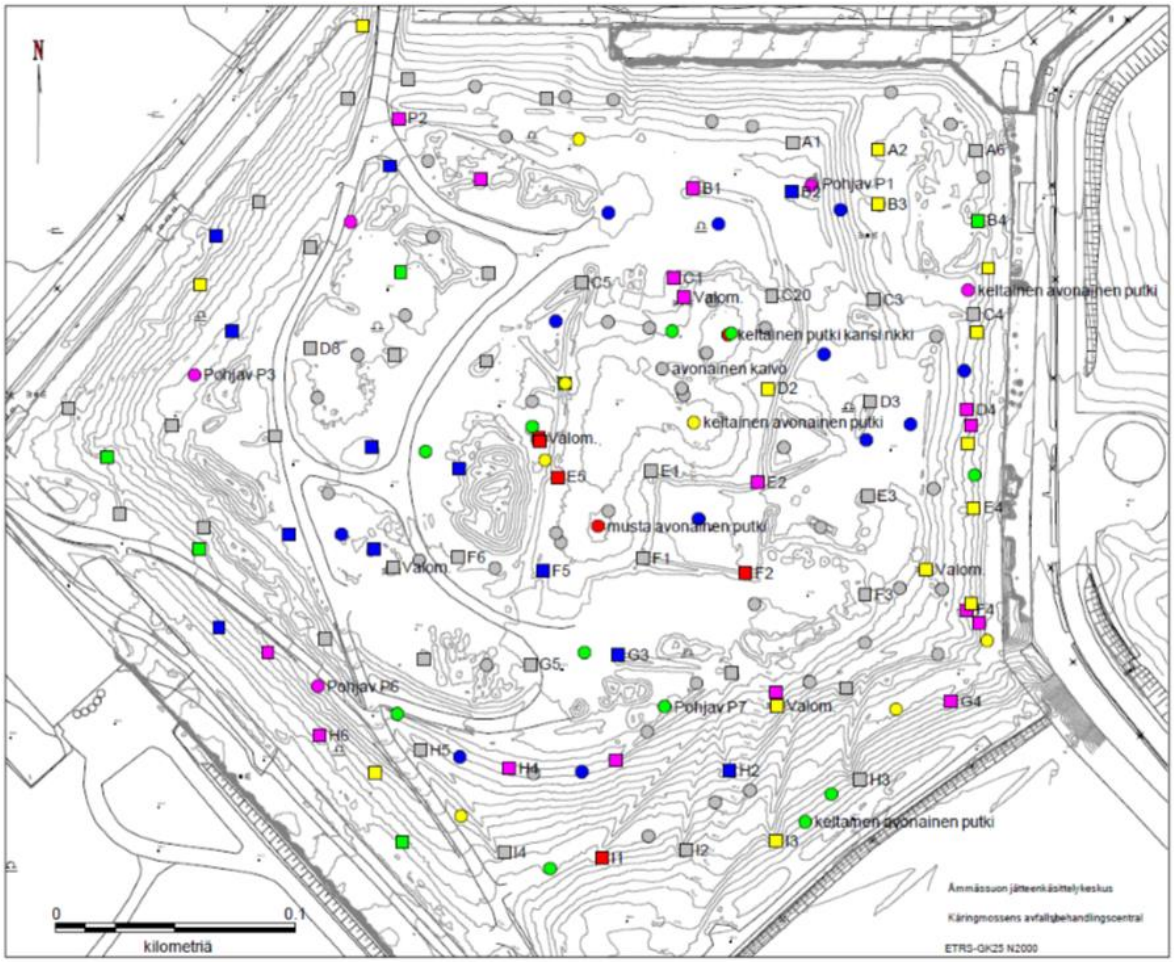
As illustrated in the Figure 2.3, the gas emissions are affected by many factors like permeability of the disposed waste, geological conditions, depth of ground water, atmospheric pressure, man-made features, landfill cover, liner systems, etc. The gas

emissions can divide mainly into surface emissions, lateral emission and emission from point sources (EA E&W, 2004).

Surface emission is the gas migration to the atmosphere from the landfill surface. This usually happens when the permeability of the cover structure is not low enough. Thus, enabling the gas to escape through the cover structure into the atmosphere. Cracks and fissures in the landfill cover structure also causes gas emissions. Cracks and fissures in the landfill cover structures are often caused due to the differential settlement of the waste underneath the cover structures and due to the drying-wetting cycles of the cover materials. Unless the emitted gases are not controlled properly, a major portion of the emitted gases may escape into the atmosphere. (EA E&W, 2004.; epaVictoria, 2018.)

When a landfill cover structure is made properly, the upward movement of the gas is obstructed. Thus, the landfill gas may be emitted laterally through a path of least resistance. This is called as lateral emission. For example, lateral emission can happen laterally through layers of low permeability soil. Coefficient of gas permeability in the migration pathway and the differential pressure over the pathway can determine the lateral emission rate. The settlements in the waste and the cover structure may change the emission pathways and the gas emission rate in the long term. Construction of a temporary or a permanent cover structure has a significant effect on the lateral emission unless the generated gases in the area are collected. In addition to this, a sudden change in the geological or hydrogeological environment can also affect the lateral emission in the landfill. (EA E&W, 2004.)

The main point sources for the gas emissions are, leaks from the gas collection system, gas collection wells, gas monitoring wells, leachate wells, and leachate holding (treatment) facilities. It is very hard to quantify the actual landfill gas emission rate from these sources without having measurement from any specific cases. (EA E&W, 2004) Figure 2.4 is the map of gas leaking points based on the methane measurements in Ämmässuo landfill during 2017.



Gas wells/light towers -
Methane concentration (ppm)

100 000	-	1 000 000	(5)
10 000	-	100 000	(16)
1 000	-	10 000	(14)
100	-	1 000	(6)
10	-	100	(12)
0	-	10	(121)

Other points -
Methane concentration (ppm)

100 000	-	1 000 000	(2)
10 000	-	100 000	(5)
1 000	-	10 000	(7)
100	-	1 000	(11)
10	-	100	(12)
0	-	10	(47)

Figure 2.4 Map of leaking points in Ämmässuo landfill (Figure: HSY, 2017c)

As illustrated in the Figure 2.4, several leaking points have been identified in the Ämmässuo landfill during the measurements taken in 2017 (HSY, 2017c). Methane emission measurements taken during this research study and the regular monitoring of HSY also identified highly concentrated methane emission around the gas collection wells.

2.4 Landfill gas control and monitoring

For minimising the potential impact on the environment that caused by the landfill gas emission, it is important to actively monitor and control the landfill gas, during the landfill operation and aftercare period. Accordingly, control measures had to be implemented to minimize the potential damage of the environment and risk to the human health. (EA E&W, 2004.) Finnish government Decree on Landfills 331/2013 gives guidelines for monitoring and controlling the landfill gas.

The key measures for the gas control are collection, treatment and containment of the landfill gas (EA E&W, 2004). According to section 8 of Finnish decree 331/2013, for controlling the landfill gas, it is stated that the generated gas in the landfills should be collected and used. If the collected gas cannot be recovered, it should be flared. (VNa 331/2013.)

Since gas pressure is a major factor for the gas emission in landfill, it could be controlled for an extent by gas collection systems. Thus, it is good to implement a gas collection system in the landfill sites where gas production takes place. Characteristics of the gas collection system can de decided according to the nature of the disposed waste and its gas generation potential. For collecting the gas from the landfill, collection wells, collection pipework, collection layers, extraction plant and condensate management system are used in the gas collection system. (EA E&W, 2004.; European Commission, EC, 2013.)

There are mainly two kinds of gas control systems such as active and passive. Combination of active and passive gas control systems are often used in the landfill sites. In the active gas control system, landfill gases are abstracted by applying the suction/negative pressure to the chosen boreholes/gas wells. Rate of biodegradation process can be enhanced by installing a gas collection system. Thus, it can result in increasing the settlement rates. On the other hand, passive gas control systems often make use of the natural pressure and convection mechanism for venting the landfill gases. Thus, the efficiency of passive gas control system is lower than an active gas control system. (USACE, 2008.)

Landfill gas is used for energy production when the landfill produces enough gases to produce the energy. The produced energy can be used for heating, industrial processes and electricity generation. If the utilisation is not viable, gas is flared by thermal oxidation. Flaring is the combustion of landfill gas to form an off-gas which is acceptable for direct discharge to the atmosphere with recovery of the energy content. (EA E&W, 2004.) Ämmässuo landfill equipped with gas collection system and a gas power plant for controlling the landfill gas. Figure 2.5 is the picture of Ämmässuo landfill gas power plant.

Figure 2.5 Ämmässuo landfill gas power plant (Picture: HSY)

Gas collection system in Ämmässuo landfill includes gas collection wells, gas control centres and gas pumping stations. Gas power plant established in 2010 can utilize all collected gases from the Ämmässuo landfill. During 2017, 35,21 milj.nm^3 gas was collected from the Ämmässuo landfill and the power plant consumed 29,63 milj.nm^3 of gas for making heat and electricity. (HSY, 2017a.)

Keeping the landfill gas under control is called the gas containment. This is often done by having the engineered covers in the sides, in the base of the site and on the top of the disposed waste. By having the engineered landfill covers, uncontrolled emission of landfill gas through the sites and base of the landfill site can be restricted. Thus, for an effective gas controlling, completed landfill sites had to covered with an engineered landfill covers with the gas collections systems. (EA E&W, 2004.)

According to Section 43 of Finnish Decree, for having a reliable information on the gas generation from all sections of the landfills, gas accumulation and migration had to be monitored regularly. Thus, gas pressure and gas volume measurement to be done in a regular interval. Components in the landfill gas such as CH_4, CO_2 and O_2 are also had to be determined periodically. Measurements had to be taken once in a month during the operational phase. During the aftercare phase, measurements had to be done only once in six months. According to Decree, condition of the gas collection system need to be examined regularly. Decree also insists, landfill operator should submit yearly reports on the gas monitoring and controlling to the supervisory authority by the end of the month February. (VNa 331/2013.)

Landfill surface emission measurement is an important part of the landfill monitoring. According to Zhongkui 2016, there is no gas permeability limits or standards for designing the landfill cover structure and the gas emission rate is considered as a design-criteria for landfill cover design in the available guidelines. Furthermore, as per the Carbon Farming Initiative (CFI), Australian guideline 2013 (cited in Zhongkui, 2016: pp.118), maximum allowed methane emission rate is 63 ml/m^2/min. Some countries like United Kingdom,

Ireland, Wales have set methane emission limits for the cover structures, which is even lower than the Australian guideline CFI, 2013. Table 2.5 describes the emission limits for temporary and permanent cover structures.

Table 2.5 Methane emission limit for landfill covers (eaWales, 2010, epaVictoria, 2018)

Type of cover	Measured flux in $mg/m^2/second$	Equivalent flux for methane in $m^3/ha/hour$	Equivalent flux for landfill gas in $m^3/ha/hour$ *	Equivalent flux for landfill gas in $litres/m^2/hour$ *
Temporary cover	0.1	5	10	1
Permanent cover	0.001	0.05	0.1	0.01

*Assuming methane at 50% v/v

Even though many new methods have been developed for measuring the landfill gas surface emissions from the cover structures, still official guidance of many countries recommend to use flux box method (or static chamber method) as an effective method for surface emission measurements. The reason is that the new technologies involve many assumptions and parameters for getting accurate results. These assumptions and parameters mainly depend upon landfill field and had to be accurately measured from the field. (Armstrong & Gregory, 2007.; Environment agency wales, eaWales, 2010.)

Surface emission measurements include two parts. In the first part, major leaking points had to be recognised with a portable gas detector. For example, FID or DP-IR instrument could be used for this measurement. Major leaking points found in this part should be sealed prior to the actual emission measurement. (eaWales, 2010.) According to the Australian guidelines, corrective actions had to be taken when the methane concentration is greater than 500ppm at the leaking points. Methane measurement at the leaking points are taken when the wind speed below 10km/hr and at a low and stable atmospheric pressure (less than 101.3kPa). (epaNSW, 2016.)

In the second part, surface emission measurements had to be done with static chamber method. For this, the area that to be measured had to divide into zones. Zone is an area having homogenous emission. Then the gas emission measurements are taken from a representative point of individual zone with static chamber method and calculate the emission for the entire area using the measurements from individual zone. This emission measurement method is relatively simple and might not require information on the landfill site variables such as prevailing meteorological conditions and physical parameters of the soil. (eaWales, 2010.)

The static chamber is an enclosed chamber, open at the base, with a sampling line connected to gas monitoring equipment at the top. The bottom of chamber is inserted into the ground for preventing atmospheric air entering the chamber. A balance valve is also connected to the top of the chamber for equalising the air pressure. Concentration of the landfill gas components in the chamber are measured over the time using a gas analyser and with a data logger. Data logger is used to collect the gas concentration data with the time. The collected data is used for analysis and calculation. (eaWales, 2010.) Figure 2.6 represents the schematic picture of a typical flux box.

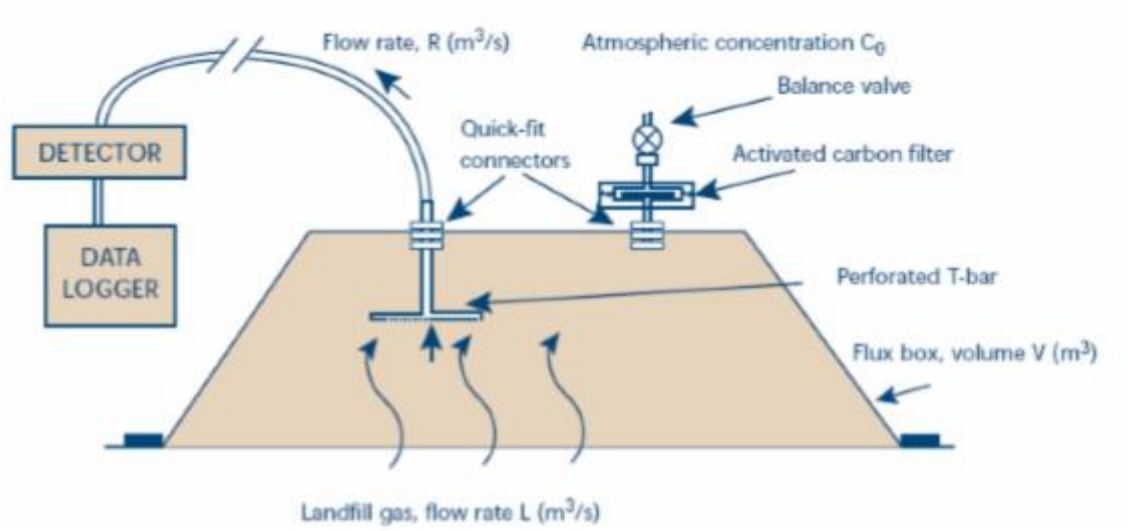


Figure 2.6 A typical flux box and methane detector set up for field measurements (Figure: eaWales, 2010)

The construction, operation and calculation details of the flux box is explained in the guidelines *Guidance on monitoring landfill gas surface emissions* by environmental agency Wales. Emission rate of each gas component can be directly calculated from the rate of change in gas concentration within the chamber over the time. Equation (1) is used for the emission rate calculation. (eaWales, 2010.)

$$Q = \frac{V}{A}\frac{dc}{dt} \quad (1)$$

where:
Q = flux density of the gas/surface emission rate (mg/m^2/second)
V = flux box volume (m^3)
A = area of flux box bottom (m^2)
dc/dt = rate of change of gas concentration in the chamber with time (mg/m^3/second)

2.5 Landfill cover structures

2.5.1 Classification of landfill cover structures

Landfill cover structure is the isolation cover constructed over the disposed waste in the landfill area to prevent the infiltration of the rain and surface water into the waste. Landfill cover structure also prevents the spreading of landfill gas, leachate and other hazardous materials to the environment. Furthermore, landfill cover structure can intensify the landfill gas collection and thereby it reduces the landfill odour and dusts that are harmful to the peoples and the environment. (SYKE, 2002.) Landfill covers are classified into four types according to the life span of the landfill cover. Four different types of landfill covers are daily cover, intermediate cover, temporary cover and permanent cover. (epaIreland, 1997.)

Daily cover is the material spread over the disposed waste on daily basis. Soil or suitable synthetic material can be used for this covering. Daily cover helps to improve the visual

appearance in the landfill working areas. It also potentially reduces the probability of windblown debris such as plastics and papers. Daily cover also significantly diminishes the accessibility for insects, birds and vermin. Furthermore, daily cover reduces the fire risk and foul odours from the landfills. (epaIreland, 1997.)

Intermediate cover is a stable material that are placed over the disposed waste for a time period, prior to the temporary landfill cover or prior to further deposit of wastes in the that particular landfill area. If in case, the wastes are not disposed in an active landfill area for about a week, generally, daily cover should be replaced with an intermediate cover. This type of cover significantly reduces the rainfall infiltration and litter. Usually, soil or similar material are used as the intermediate cover material. Intermediate cover is usually made with a thickness of 300 mm in depth than a daily cover. (epaIreland, 1997.)

Temporary cover is constructed over the completed landfill areas prior to the permanent cover installation. Later, temporary cover can be the part of the permanent cover construction. Temporary cover prevents the landfill gas emission and the infiltration of rainfall / lateral egress of leachate. It is generally constructed, when there is a significant gas formation in the waste and the waste has to allow settle for more than two years. (SYKE, 2008.; epaIreland, 1997.) After closing the waste deposition in the landfill, the waste mass may undergo significant differential settlement. During the preliminary years of biodegradation, settlement will be quite rapid. This usually creates major cracks in the cover structure that is installed above the waste. Therefore, it may not be economical to make the permanent cover structure during settlement period. Thus, it is better to allow the cover structure to settle as long as possible before the installation of the permanent cover structure. Otherwise, settlement may affect the efficiency of the permanent cover structure. The speed of the settlement, quantity and the duration depend upon many factors such as moisture content, temperature, waste quality, degree of compaction done in the waste before closing and the mixing of waste, etc. If the waste decomposes effectively, the major settlement may complete in almost 10 years. (SYKE, 2008.; epaIreland, 1997.) Temporary cover structure is a near-impermeable barrier. The recommended value of coefficient of water permeability for the impermeable layer of the temporary cover structure is $k<1x10^{-8}$ m/s. Geosynthetic clay liners (bentonite mat) or 0.5m thick compacted soil ($k<10^{-8}$m/s) are usually used as temporary cover structure. (SYKE, 2008.; epaIreland, 1997.)

Permanent cover (final cover) is constructed above the temporary landfill cover after the significant biodegradation and settlement of the waste is completed. Permanent cover is constructed to a designed height considering the future need of the landfill site. Purpose of the permanent cover is same as that of the temporary cover, such as preventing the landfill gas emission and infiltration of the rainfall. The required coefficient of water permeability is $k<1x10^{-9}$m/s which is lower than the temporary cover. (SYKE, 2008.; epaIreland, 1997.) Some countries have more strict gas emission limits for the permanent cover than the temporary cover (epaVictoria, 2018). The gas emission values of the permanent cover and temporary cover are given in table 2.5. Permanent cover of the landfill is designed and constructed to last for a long period of use (epaIreland, 1997).

2.5.2 Finnish guidelines for landfill cover structures

Finnish Government decree on landfills (VNa 331/2013) contains guidelines regarding landfill management and construction. According to decree VNa 331/2013, a landfill cover structure had to be constructed at hazardous and non-hazardous landfills when the waste filling area reaches its capacity. According to the regulations, landfills with inert waste does not need a landfill cover. But the hazardous and non-hazardous landfills should have a cover structure with a gas drainage layer, impermeable layer, water drainage layer and a top soil cover. In addition to this, hazardous landfills require an artificial sealing layer. Table 2.6 shows the required structural layers in the hazardous and non-hazardous landfills according to the decree VNa 331/2013. The permit authority can ease the requirements for the cover structure based on the overall assessment. Decision on the requirements depends on the impact of the landfill on human health and the environment. Furthermore, as per the regulations, clean surface water within the landfill site and external surface runoff water had to keep separate from the waste, landfill leachate and the other contaminated water. The order of the structural layers can be altered for reasonable justification. (VNa 331/2013.)

Table 2.6 Required cover structure layers needed in the hazardous and non-hazardous waste landfills (VNa 331/2013)

Layer	Landfill for non-hazardous waste	Landfill for hazardous waste
Top soil cover ≥1m	Required	Required
Drainage layer ≥0.5m	Required	Required
Impermeable layer≥0.5m	Required	Required
Artificial sealing layer	Not required	Required
Gas drainage layer	Required	As necessary

According to the Finnish decree VNa 331/2013, the only requirement for the layers is its required minimum thickness. However, the impermeable liner is designed to act as a barrier of low water permeability which provides also low gas permeability. A typical requirement of the impermeable layer is that coefficient of water permeability should be lower than 1×10^{-9} m/s for the permanent cover. (Leppänen, 2018.)

2.5.3 Landfill cover structure layers

In practice, landfill cover structure (final or temporary cover structures) contains many layers and each layer has its own objective and requirements. Figure 2.7 is an example of the cross section of a landfill cover structure.

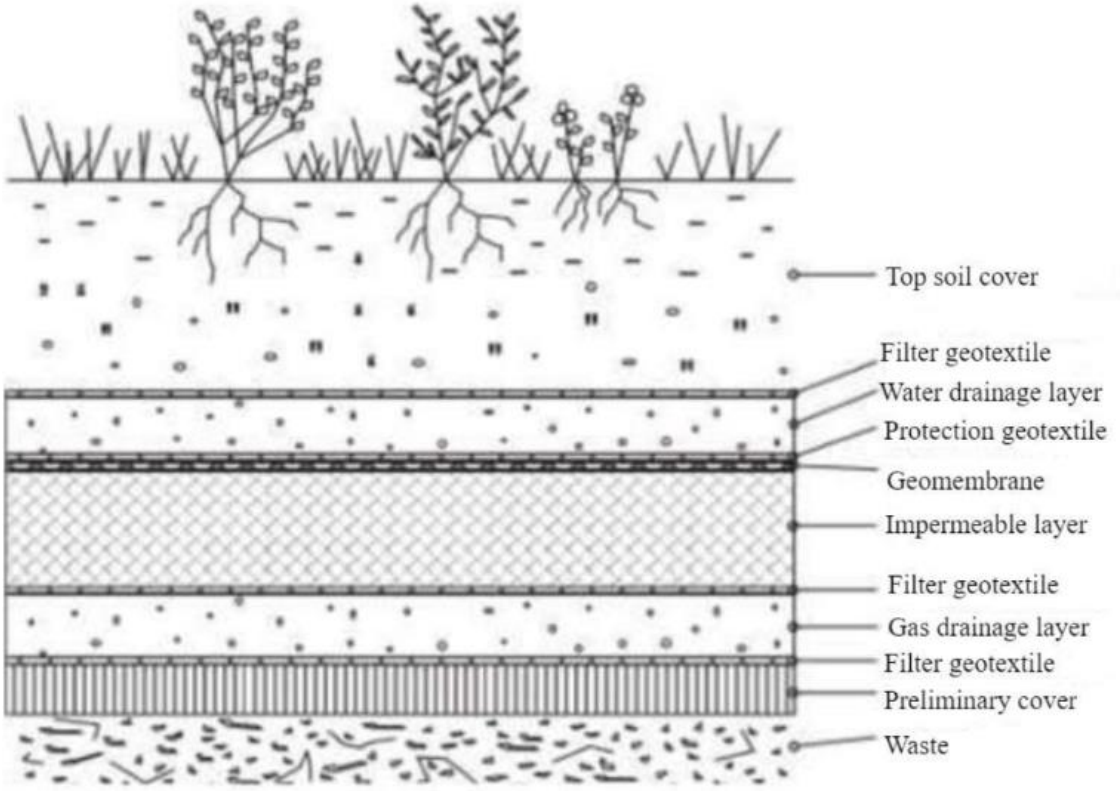


Figure: 2.7 Example of landfill cover structure (picture: SYKE, 2002*)*

As illustrated in the figure 2.7, a typical cover structure of a landfill area that is stopped from the practice can have the following layers (from bottom to top):

1. Preliminary cover
2. Geotextile if needed
3. Gas drainage layer with high permeable material
4. Separation geotextile if needed
5. Impermeable layer
6. Geomembrane
7. Geotextile if needed
8. Water drainage layer
9. Geotextile if needed
10. Topsoil cover
11. Vegetation layer

As described in the earlier sections, the purpose of the whole cover structure is to control the infiltration of the rain and surface water into the waste and thereby to control the development of leachate and other pollutants migration into the environment. It helps to separate clean water and generated leachate. By having a cover structure, landfill gas collection from the landfills can be intensified and the problems due to gas emission can be reduced. The landfill cover structure had to be chemically, and physically resistant. The slope and the other properties of the cover structure need to stable during the life span of the cover structure. While designing a landfill cover structure, erosion due to water and wind, frost, freezing thawing cycles, drying wetting cycles, penetration of plant roots into the structure, impacts of gnawers and possible accident situations have to be considered. Cover insulation

structure should keep its insulation properties against the differential settlement and had to fulfil the traffic requirements of the construction site during its lifetime. (SYKE, 2002.)

The cover structure is situated above the waste mass. Before the construction of the insulation structure, waste mass should be prepared with enough slope to keep the surface dry and stable against the slipping, considering the waste mass settlement. If required, the waste mass can also be compressed. (SYKE, 2002.)

Preliminary cover above the compressed waste embankment, cover the waste thereby preventing the spreading of the waste into the environment. It also prevents the mixing of waste with the material of layer above it. Preliminary cover works as a load bearing surface and evenly transferring pressure from the compaction of layers above it. This layer leads the landfill gas into the gas drainage layer. Preliminary cover is made with different type of materials such as natural soil, contaminated soil, recycled materials, etc that satisfy the landfill construction requirements. This layer should have enough slope to account the surface run off and the slope stability. (RTS, 2018.) Minimum recommended inclination for the landfill cover for the surface runoff is 5%. Therefore, the inclination of the preliminary cover should be greater than 5%. However, the slope of the layer depends upon the friction angle of the construction material. Typical maximum slope is 1:4 to 1:3. Estimated settlement also had to be considered for the slope calculation. Typical layer thickness of the levelling layer is 0.3m and minimum thickness is two times the maximum grain size of the construction material. (InfraRYL, 2018.)

Geotextiles separate the materials of the one layer from the materials of another layer. Installation of geotextiles between two layers is necessary if there is a need to prevent the penetration of fine materials into another layer. Material of the geotextile is selected based on the purpose and durability. Thus, the geotextile material should be resistant against the aggressive components of landfill gas. Instead of geotextile, soil which satisfy filter layer criteria could also be used in this layer. Recommended minimum percent open area (POA) of woven geotextiles using in landfill is greater than or equal to 10% for preventing biological blockage. If there is no chemical loading in cover structures, geotextiles with NorGeoSpec class such as N3 or N4 can be used based on the grain size. (RTS, 2018.)

Gas drainage layer gathers the landfill gas and provides a load carrying base to the impermeable layer. Coarse grained materials which is suitable for load carrying layer and having high permeability are recommended for this layer. In addition, materials should have enough resistance against aggressive landfill gas components and leachate. Drainage mats also can be used as material for gas collection layer. From the economical perspective, levelling layer can be made as gas drainage layer with a suitable material. In case, when there is no gas generation from the waste, gas drainage layer is not needed. If the gas formation is very little, gas channels or membranes can be used instead of gas drainage layer. (RTS, 2018.) For intensifying gas formation, a watering layer can be included in the gas drainage layer or below it (SYKE, 2002). Fine materials (<0.063mm) that are used for making the gas drainage layer should be less than 20%. Recommended minimum layer thickness is 0.1m and the minimum layer thickness had to be two times the maximum grain size of the construction material. At the location of the gas collection pipes, the minimum thickness of the gas drainage layer is 0.3m. (InfraRYL, 2018.)

Impermeable layer works as water and gas barrier in the cover structure. Even though this layer is named as impermeable layer, indeed the layer is not fully impermeable. In practise this layer exhibits low permeability. This layer reduces the rain water absorption into the waste and prevents the escaping of landfill gas in uncontrolled way to the environment. Cracking risks in the impermeable layer due to drying and differential settlement of the waste mass should be considered while designing this layer. Construction material that is used in this layer should not lose its properties due to freezing-thawing, wetting-drying cycles and differential settlement of waste under the layer. Minimum layer thickness of this layer is 0.5m. Water and gas permeability of the layer should be low enough to prevent water infiltration and gas emigration. Water permeability requirement usually mentioned in the landfill environment permit. In a permanent landfill cover structure, for the impermeable layer, typical value of water permeability requirement is $k \leq 1.10^{-9}$ m/s. In a temporary landfill covers, the recommended coefficient of water permeability is $k < 1.10^{-8}$ m/s (SYKE, 2008). Compatibility of the granular materials can be determined by preliminary tests. Materials like clay, soil-bentonite mixture, fiber-clay, bentonite mat, waste materials and other industrial by-products which could satisfy criteria can be used for the impermeable layer construction. (RTS, 2018.; InfraRYL, 2018.; SYKE, 2008.)

Geomembranes are thin, flexible, fluid-impermeable synthetic or bituminous based product. Geomembrane is usually installed above the impermeable layer in the cover structure. Geomembrane is used to prevent the water penetration into the structure and intensifying gas collection in landfill cover structures. It can also prevent the penetration of the roots into the impermeable layer. Stability against sliding between the geomembrane and soil layer should be checked and the joints should be firmly joined. Geomembrane installation is a mandatory requirement in the cover construction of hazardous waste landfill. However, it can also be provided in the non-hazardous landfills if necessary. Geomembrane should have strength to withstand the deformation due to the differential settlement. (RTS, 2018.) Selected geomembrane material should be resistant against chemical, biological and mechanical stresses during the lifespan of the cover structures without losing its properties. Geomembrane should be installed to the other nearby structures with water and gas tight. Minimum thickness of the membrane that could weld is 1.5mm. There are different types of geomembranes such as HDPE (High Density Polyethylene), LLDPE (Linear Low Density Polyethylene), FPP (Flexible Polypropylene), EPDM (Ethylene Propylene Diene Monomer), etc. Usually, LLDPE membrane with friction coating is used in the landfill cover structures. (InfraRYL, 2018.)

Drainage layer collects and rapidly removes the drained water from the landfill cover structure thereby it reduces the water pressure above the impermeable layer. Drainage layer protects the impermeable layer from frost and root penetration. This layer should have enough storage capacity for the water during heavy rain and thawing. Material of this layer should be mechanical and chemical resistant. (RTS, 2018.) The minimum thickness of the layer is 0.5m and required minimum slope is 5%. The recommended water permeability is $k \geq 10^{-3}$ m/s. (InfraRYL, 2018.)

Top soil cover is constructed for frost protection and preventing the layers below it from drying. For achieving enough frost protection and preventing the impermeable layer from root penetration, more layer thickness is needed in the top soil cover. Thicker top soil cover can reduce water absorption into the structure and manage the surface runoff. This layer will give water to plants and protect the underlying layers from the vegetation roots. The material

used for the top soil cover had to be surface erosion resistant and should enables water retention of the natural soil. This layer should have enough water storage capacity for heavy rain and the material should be high in water permeability. Average water permeability coefficient is $k \geq 10^{-6}$ m/s. Amount of fine materials (<0.063mm) should be less than 10%. Total thickness of top soil cover has to be 1.0m. It includes 0.8m thick bottom part and 0.2m top part vegetation layer. (RTS, 2018.; InfraRYL, 2018.)

Vegetation layer should work as a suitable soil layer for the vegetation. The layer should satisfy the landscape objectives. Vegetation layer can reduce water getting into the structure through evaporation and reduce surface erosion. However, vegetation roots may make damages to the impermeable layer by penetrating the roots into the structure. Therefore, shallow rooted vegetations are recommended and thickness of the layer should be selected considering the root penetration. The root penetration can be prevented by root mat or geomembrane. The vegetation layer can allow maximum surface runoff. However, this layer should be erosion resistant and should have load bearing capacity. (SYKE, 2002.) Typical depth of a vegetation layer is 200mm. However, the selection of layer thickness should be done considering the root penetration, landscaping and after use plan of the landfill. (InfraRYL, 2018.)

2.6 Gas flow through landfill cover

Understanding of the gas transport mechanisms in landfills is very important for evaluating the performance of landfill cover structure in preventing gas emission to the atmosphere. Gas emission in landfill cover is highly dependent on the landfill cover properties. (Kallel, 2004.) Since natural soil is more environment friendly, landfill cover structures are usually made with natural soil. The cover structures usually are in unsaturated condition due to the infiltration of rainwater into the structure. However, it will not be in fully saturated condition, since the structures are designed with enough slope to reduce water infiltration into the structure. (Maciel and Jucá, 2006.; *Zhongkui, 2016.*) The construction material used in Ämmässuo cover structures in this study is Municipal solid waste incineration bottom ash (MSWI BA). This kind of materials shows similar kind of hydraulic properties as natural soil aggregates with respect to the grain size (Sormunen, 2017). Therefore, it is assumed that the gas and water flow properties through the material MSWI BA would be similar as through the natural soil aggregates.

Gas phase in an unsaturated soil can exist either as a continuous phase or in the form of occluded bubbles (Fredlund, 2012). The gas phase generally becomes continuous when it reaches the capillary entry pressure ($P_{c,entry}$). Capillary entry pressure ($P_{c,entry}$) is the sufficiently high gas pressure to force gas into the largest pores of the soil. (Hildenbrand et al., 2002.) Figure 2.8 shows the schematic representation of the conceptual stages of the gas flow through the porous medium.

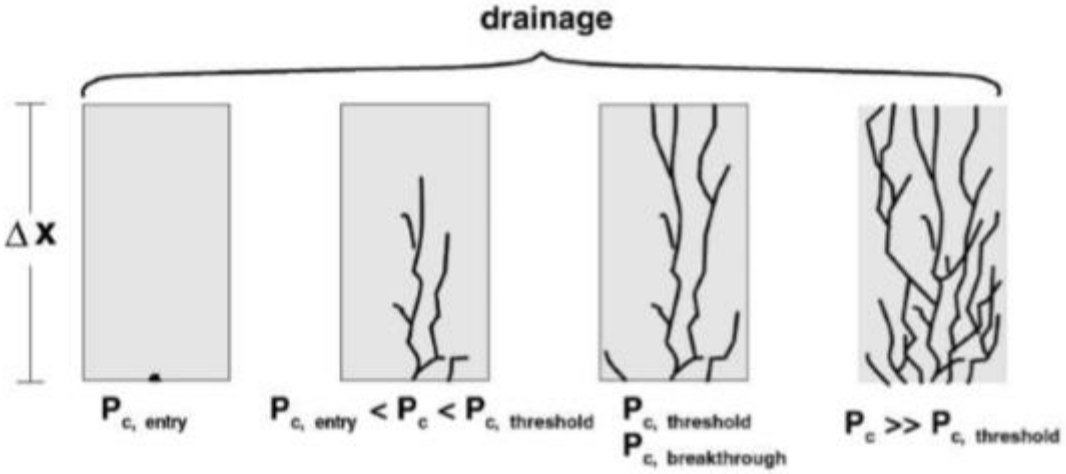


Figure 2.8 Conceptual stages of capillary gas breakthrough process in fine grained rocks (Figure: Hildenbrand et al., 2002)

When gas pressure increases and reaches gas breakthrough pressure ($P_{c,breakthrough}$) or threshold pressure ($P_{c,threshold}$), gas will make a flow path across the pore system with a small portion of interconnected largest pores which have least resistance to capillary displacement. Gas breakthrough pressure is the excess pressure in the gas phase at which water phase was displaced to an extent and continuous gas phase forms across the pore system. If the pressure increases further, more flow paths will be developed across the porous medium and the flow will change from capillary to viscous dominated. When the gas pressure is between capillary entry pressure and gas threshold pressure, a partial saturation of pores with gas occurs in the soil. When the gas pressure is above gas threshold pressure, gas leakage or emission starts from the soil. (Zhongkui, 2016.; Hildenbrand et al., 2002.)

Landfill gas flows through the landfill cover soil mainly by the transport mechanisms, advection and diffusion. Pressure gradient causes advection and gas concentration gradient between waste and atmosphere causes diffusion. The rate of gas movement is generally faster for advection than for diffusion. (Wickramarachchi et al., 2011.)

In advective flux, when there is a total pressure gradient in the soil, gas flow will happen from the point with higher pressure to a point with lower pressure through a path of least resistance. Relatively small total pressure gradients result in larger advective gas fluxes than diffusive gas fluxes. In landfills, due to low permeability of landfill cover and high amount of gas generation from waste, there exists a high-pressure gradient between inner parts of landfill and atmosphere. This pressure difference makes advective flow possible. (USACE, 2008.)

According to Cunningham & Williams (1980 cited in Scanlon et al., 2002: 301), total pressure gradient is the driving force for advective gas flow. And the viscosity of the gas can create the resistance to flow. When the mean free path of the gas molecules is much less than the pore radius and the soil particle size, advection becomes dominant under a total pressure gradient. This results in the dominance of intermolecular collisions relative to collisions between gas molecules and the pore walls. The mean free path is the average distance travels by a gas molecule before it collides with another gas molecule. Pore radius is the average distance between soil particles in a dry porous medium. Mean free path is inversely

proportional to the average gas pressure. Low mean free paths in relation with pore size, may happen in dry, coarse-grained medium and/or under high mean pressure. (Scanlon et al., 2002.)

When the average pressure and/or the size of the pore decrease, flow will change from advective flux to diffusive flux. Molecular diffusion can happen in a system if there is a difference in the concentration between two different points. Direction of the gas flow diffusion will be towards where its concentration getting decreased. Air and water in the voids of a soil can act as conducting medium for diffusion processes. At the same time, the diffusion path and cross-sectional area is highly dependent on the soil structure. Since, the concentration of a volatile constituent in the landfill gas will always be more than that of the surrounding atmosphere, the landfill gas constituent will tend to migrate to the surrounding atmosphere. Gas-phase diffusion occurs due to gas molecule-molecule and molecule-wall collisions. As per the kinetic theory of gases, in an isothermal, isobaric system, gas molecules procure same kinetic energy. Thus, lighter gas molecules can attain higher velocities than heavier gas molecules. Fast diffusion of the lighter gas molecules develops pressure gradient and can result in diffusive flux. Wind at landfill site can keep the surface concentration of landfill gas around zero. Thereby maintaining the concentration gradient between the surface and inside the landfill. This will make possible migration of gases to the surface. (USACE, 2008., Scanlon et al., 2002.; Fredlund, 2012.)

Even though, various models have been used to describe the gas flow through porous media, Darcy's law and Fick's law are generally used for explaining the mechanism (Webb, 2006). Darcy's law is used to model advective gas flow and Fick's law has been used to model molecular diffusion. (Scanlon et al., 2002; Fredlund, 2012). According to Darcy's law, the driving potential of advective flow is the pressure gradient (Fredlund, 2012) and the advective gas flow rate can be calculated with equation (2)

$$Q_g = \frac{K}{\upsilon_g}\frac{p_1 - p_2}{L}A \qquad (2)$$

Where
Q_g = volumetric gas flow rate (m^3/s)
K = Intrinsic permeability of the porous medium (m^2)
υ_g = dynamic viscosity of the gas (Pa s)
p_1 = inlet pressure (Pa)
p_2 = outlet pressure (Pa)
A = area of cross section (m^2)
L = thickness of the layer(m)

Intrinsic permeability K is a measure of flow properties of a porous medium. It is a relevant concept in unsaturated soil mechanics that the value of intrinsic permeability is used to convert the saturated water coefficient of permeability to coefficient of gas permeability of a dry soil with same porosity. It is calculated using the pore fluid properties. Intrinsic permeability is an average property of a medium, which measures the ability of a porous medium to conduct fluid through it. (Fredlund, 2012.)

According to Fredlund, 2012, the ability of conducting gas through an unsaturated medium can be described by coefficient of gas permeability k_g(m/s) and it can be calculated by the equation (3)

$$k_g = -\frac{\rho_g g}{\upsilon_g} K \quad (3)$$

Where
K is intrinsic permeability (m^2)
g is gravitational acceleration (m/s^2)
ρ_g is density of gas (kg/m^3)
υ_g is dynamic viscosity of the gas (Pa s)

Coefficient of gas permeability is highly dependent on the degree of saturation of the soil. Coefficient of gas permeability decreases when degree of saturation increases. (Fredlund, 2012.) With respect to the degree of saturation, k_g can be calculated using the equation (4).

$$k_g = k_d(1 - S_e)^{1/2}(1-S_e^{\frac{1}{q}})^{2q} \quad (4)$$

Where
k_d is the gas permeability of dry soil
S_e is effective degree of saturation with respect to the water phase
q is the fitting parameter related to the pore size distribution.

Diffusion process is driven by the concentration gradient. According to Fick's first law, the rate of mass transfer of a diffusing substance through a unit area is directly proportional to the concentration gradient of the diffusing substance. According to Fredlund, 2012, mass rate of the gas diffusing across a unit area of the soil voids can be calculated using equation (5)

$$\frac{\partial M}{\partial t} = -D\frac{\partial C}{\partial y} \quad (5)$$

Where
$\frac{\partial M}{\partial t}$ = Mass rate of the gas diffusing across a unit area of the soil voids
D = Coefficient Diffusion
C= Concentration of the diffusing gas in mass per unit volume of the soil voids
$\frac{\partial C}{\partial y}$= Concentration gradient in the y-direction

According to Fredlund, 2012, often specific compounds can exhibit different diffusion coefficients. Diffusion coefficients are the rate constants for the mode of transport. And thus, it can be used to quantify the speed of a compound taking for diffusion. Concentration of gas in a unit volume of soil is dependent upon the density of gas, degree of saturation and porosity of the soil. It can be determined by the equation (6)

$$C=\rho_g(1 - S)n \quad (6)$$

Where
C = concentration of gas
ρ_g = density of gas in the soil
S = degree of saturation
n = porosity of the soil

2.7 Factors affecting gas emission through landfill cover

The main design criteria in the landfill cover design is the coefficient of water permeability of the impermeable layer. The typical required coefficient of water permeability value for permanent landfill cover is $k < 1x10^{-9}$ m/s. (SYKE, 2008). However, studies show that hydraulic requirement for the compacted soil covers may not be enough to control the landfill gas emission for the landfill cover. Thus, in addition to the coefficient of water permeability, there are many other factors also had to be considered for preventing gas emission through landfill cover. From the earlier studies, it has been noticed that, coefficient of gas permeability, moisture content, pressure, degree of compaction, thickness of the impermeable layer, and cracks in the layer can affect the gas emission through the landfill cover. (Zhongkui, 2016.)

Effect of coefficient of gas permeability

Gas emission rate depends upon coefficient of gas permeability and the emission rate increases with increase of coefficient of gas permeability. Coefficient of gas permeability differs from the coefficient of water permeability for same soil with same degree of saturation. These two coefficients of permeabilities vary differently with variations in degree of saturation. Coefficient of water permeability increase with increase of degree of saturation and coefficient of gas permeability decrease with increase of degree of saturation. Coefficient of gas permeability is considered as a measure of the gas conductivity of a medium. However, the value of gas permeability changes with different factors such as degree of saturation, layer thickness, cracks, etc. (Fredlund, 2012.; Meggyes et.al 1998.; Zhongkui, 2016.) Figure 2.9 shows the computed gas emission rates with different gas permeabilities in a clay layer of thickness 0.6m and applied gas pressure of 5 kPa.

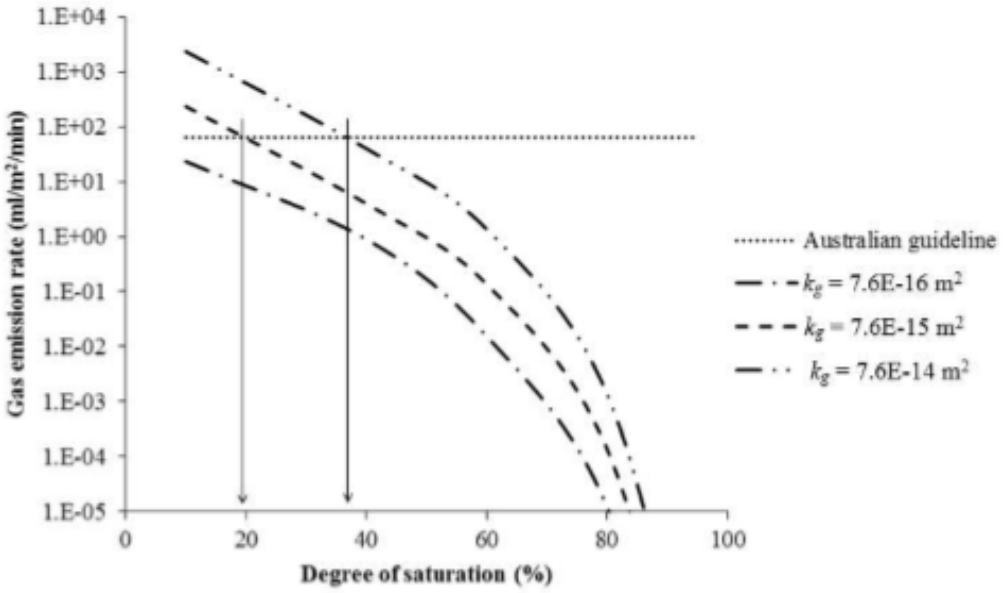


Figure 2.9 Computed gas emission rates at different gas permeabilities(k_g) of a clay layer at gas pressure=5kPa and layer thickness = 0.6m (Zhongkui, 2016)

Effect of moisture content

Moisture content or degree of saturation is a strongly influencing factor in the landfill gas emission. When the degree of saturation increases, gas conductivity will decrease. This is due to the lack of interconnected gas flow path since more water occupies in the soil voids and obstruct the gas flow. The coefficient of gas permeability reaches its maximum value when water saturation degree is low. (Fredlund, 2012; Zhongkui,2016.) Figure 2.10 shows the variation in calculated and measured gas emission rate for different degree of saturation.

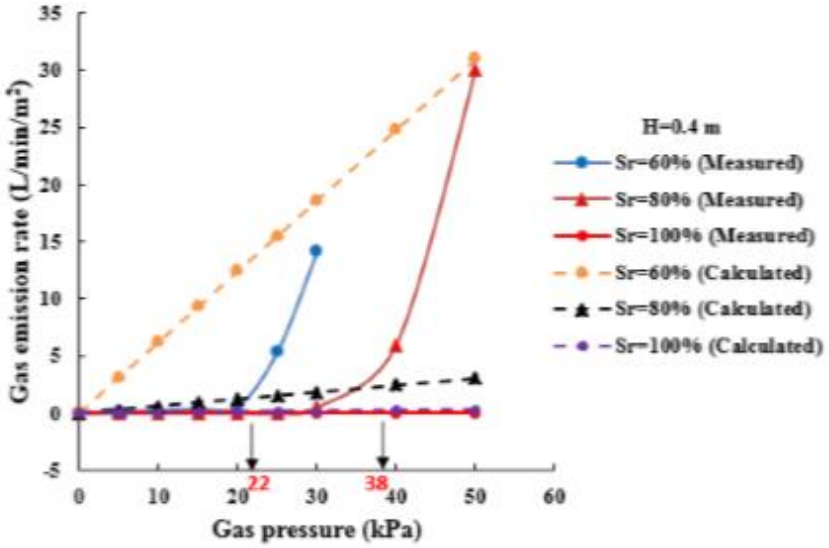


Figure 2.10 Relationship between applied gas pressure and gas emission rate at three degrees of saturation of a clay layer (Picture: Zhongkui, 2016)

According to the figure 2.10, when the gas pressure reaches a certain level(>22kPa), the measured gas emission rate becomes higher for lower degree of saturation than for a higher degree of saturation.

Effect of pressure

Changes in pressure is a significant factor in the change of gas emission. Barometric pressure variations and landfill gas pressure variations make changes in the emission rate considerably. When the pressure gradient increases under the layer, gas emission rate will increase. When gas pressure is in low range, emission will be almost zero. Gas emission starts when the gas pressure increases and reaches the gas breakthrough pressure, Value of gas breakthrough pressure varies with different degree of saturation, compaction and porosity of the soil. When the degree of saturation and compaction increases, gas breakthrough pressure also increases. With the increase of porosity, breakthrough pressure will decrease. Keeping the gas pressure below the gas breakthrough pressure is very significant method to reduce gas emission. (Fredlund, 2012; Zhongkui, 2016.) According to McBean et al., 1995, reported landfill gas pressure is usually below 10kPa (cited in Zhongkui, 2016: pp.115).

When the barometric pressure decreases, difference in pressure between the atmosphere and gas pressure below the impermeable layer will increase. This can result in a positive pressure gradient and an increase the gas emission from the landfill. Studies show that change in gas emission rate happens faster with the changes in the barometric pressure. Figure 2.11 explains the changes in methane concentration with the increase in barometric pressure during the passage of a cold front.

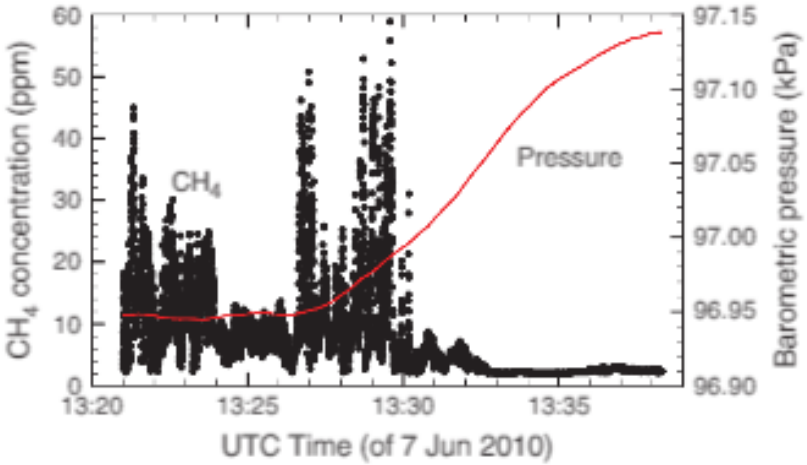


Figure 2.11 The response of atmospheric methane concentration to an increase in barometric pressure(red line) (Picture: Xu et al., 2014)

According to the Figure 2.11, when the barometric pressure increases from 96.95kPa to 97.14kPa, methane concentration decreased from 50ppm to below 10ppm. For a 0.19kPa change in barometric pressure, there is almost 40ppm change in the methane concentration. When the barometric pressure started to increase, landfill gas pressure gradient between the atmosphere and inside the landfill decreases and result in less methane emission to the atmosphere. It also shows, change in the concentration of the methane was very quick and

happened in about 3 minutes after the barometric pressure started to increase. (Xu et al., 2014.)

Effect of degree of compaction

Gas emission rate reduces with the increase in degree of compaction. This is due to the reduction of interconnected gas flow path with the compaction. However, according to Zhongkui, 2016, reduction in gas emission rate is more dominant in soil with relatively higher water saturation. This happens during the compaction when the soil particles compress more with relatively higher degree of saturation than lower. (Zhongkui, 2016.) Figure 2.12 shows effect of degree of compaction on gas emission rate.

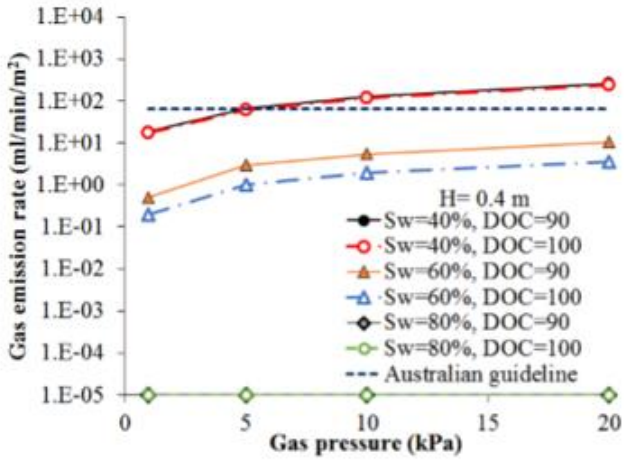


Figure: 2.12 Effect of degree of compaction on gas emission rate for a clay layer (H=0.4m) (Picture: Zhongkui, 2016).

Effect of thickness of the impermeable layer and grain size distribution of the soil

According to Zhongkui, 2016, gas emission rate decreases with increase of layer thickness. Zhongkui study also shows that the soil with larger particle size have higher gas emission rate compared to fine grain soil. However, according to Zhongkui, gas emission can be effectively reduced by increasing the thickness of soil layer than by using a soil with reduced grain size. Figure 2.13 explains the gas emission rate variation with layer thickness and grain size particle size of soil.

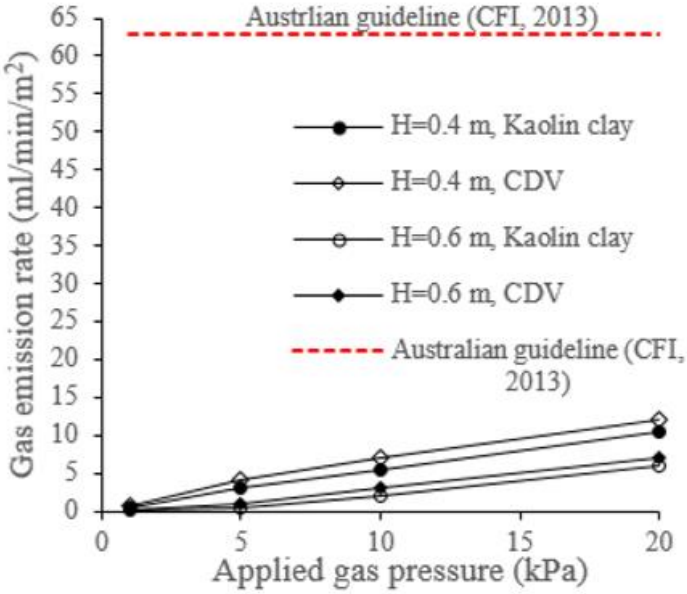


Figure 2.13 Effect of thickness on gas emission rate with layer thickness (Picture: Zhongkui,2016).

CDV mentioned in the figure 2.13 is Completely Decomposed Volcanic, which is a silt seen in Hong Kong. Zhongkui suggests that if finer particles are unavailable, it could be compensated by increasing the thickness of the layer with available soil to decrease gas emission rate. (Zhongkui, 2016.) However, the soils used in Zhongkui study was comparatively small grain soils. According to Rakennustietosäätiö, 2018, for making impermeable layer with natural soil, amounts of finer particles < 0.063mm should be greater than 20% and amount of clay (<0.002mm) should be greater than or equal to 14%. Furthermore, equation (2) for gas emission also emphasize that gas emission rate is inversely proportional to the thickness of the layer.

Effect of temperature

Soil temperature has a significant effect on the gas emission. When the temperature of the soil increases, there will be expansion in the soil, thus resulting in cracks in the soil layer. These cracks make easy pathway for the gas migration and thus gas emission increases. (Teclehaimanot, 2005.) According to Rowe, 1998 (cited in Yesiller, N. & Hanson, J.L. 2003: pp.2), temperature upto 70˚C have been measured for wastes, leachate, and landfill gas. Increase in temperature, increases the rate of degradation of the waste and gas generation. (Wang, 2012). Desiccation cracks are developed in the bottom part and upper part of the landfill cover structure due to the high temperature in the waste and atmosphere (RTS, 2018). Thus, these factors can increase the gas emission. On the other hand, methane oxidation is more in higher temperature such as 25˚C to 30˚C. Thus, at temperature 25˚C to 30˚C, methane emission will be reduced partly. Methane oxidation is the process takes place in the landfill soil by a group of methanotrophic bacteria that lives in the landfill cover soil. Those aerobes oxidize methane under natural conditions to produce CO_2, water, and microbial biomass. Other organic compounds in landfill gas also can be partially or fully degraded by methanotrophic bacteria. (Abushammala et al., 2014.) Another gas emission reduction factor is the gas viscosity, which increases with increase in the temperature. (Scanlon et al., 2002.)

During the colder temperature, shrinkage of the soil reduces the pore size thereby decreases the gas emission through landfill cover. Frozen soil and snow give a physical barrier against surface gas emission. However, freezing and thawing cycles may results cracks in the surface and thereby gas emission increases. (Teclehaimanot, 2005.)

Effect of cracks

Cracks are easy pathway for the gas flow. Due to evaporation of the water particles into the atmosphere, desiccation cracks are developed in the upper part of the soil layer. There is also a possibility of cracking at the lower part of the impermeable layer due to the high temperature of waste and landfill gas (RTS, 2018). During the degradation of heterogenous waste in the landfill, there will be a considerable change in the volume and thickness of the waste. This can be different in different places within the landfill, thus may result in the differential settlement in the landfill cover structure. Figure 2.14 is the schematic representation of deformation of a landfill cover due to the differential settlement.

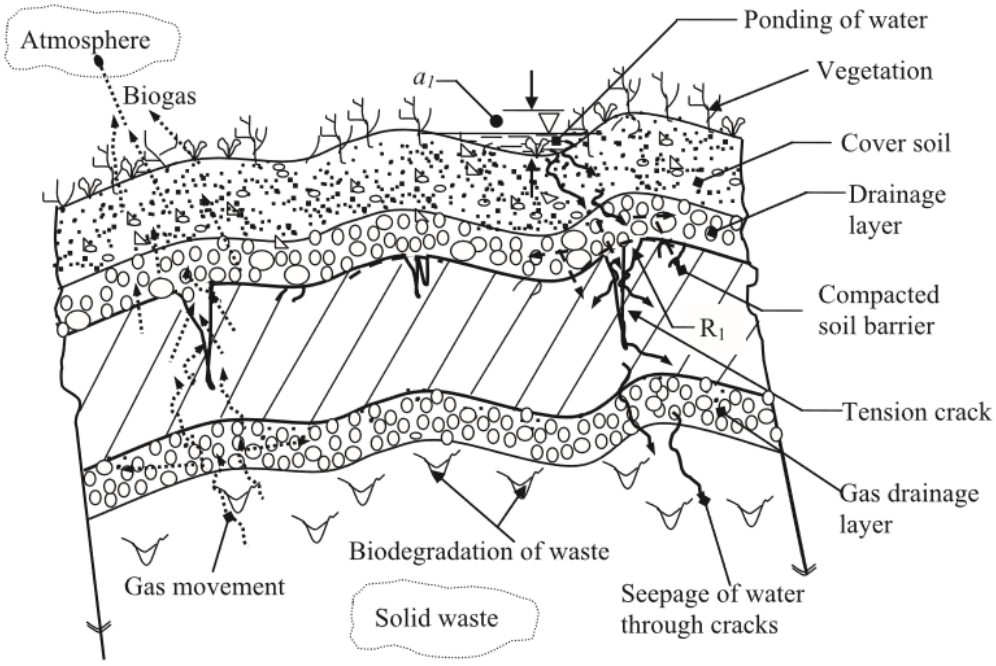


Figure 2.14 Schematic representation of deformation of landfill cover due to differential settlement in waste (Picture: S.Rajesh et al., 2014)

When the tensile strain due to differential settlement exceeds the ultimate strength of the soil layer, tension cracks develop in the landfill cover layers. This phenomenon should be considered in soil selection so that the soil with least cracking potential can be used to address this problem. Geosynthetic reinforcements can be also used to address this issue. To minimize the vertical penetration of the cracks, each sublayer should be well arranged in the design and construction. (Rajesh et al., 2014.; Viswanandham et al., 2008.)

Cracking can considerably increase the gas emission rate and gas permeability. Gas emission rate in the cracked soil depends on the effective thickness of the cracked soil layer and gas pressure. The effective thickness is the difference between the total layer thickness and crack depth. Gas emission will also increase with the increase in crack depth. Thus, only the

uncracked soil layer acts as a barrier for gas emission. By increasing the thickness of the impermeable layer gas emission caused by the cracking can be reduced. (Zhongkui, 2016.)

In additions to the above factors, gas emission is also influenced by the variations in the groundwater table. When the groundwater table rise, it can force the landfill gas to move upward. Upward movement of the landfill gas can lead into the gas emission from the cover structure (ATSDR, 2001.)

Considering the cracking effect in the clay soil layer, Zhongkui (2016) suggested the clay layer with thickness of 0.75m to meet the limit of the gas emission rate set by the Australian guideline. Gravimetric water content in the tested clay layer was around 30%. Another result from the Zhongkui (2016) study shows, clay layer thickness with 0.6m and degree of saturation 40% also could satisfy the Australian limit for the cracking effects. Australian guideline for methane emission limit is 63ml/m^2/min. (Zhongkui, 2016.) However, other countries have a lower limiting value than Australian limit and it is 16.67 ml/m^2/min for temporary and 0.167 ml/m^2/min for permanent cover structures. (eaWales, 2010) Therefore, for achieving the lower emission rate than Austrian limit, more thickness and/or more degree of saturation might be needed. However, increasing the degree of saturation is not desirable in landfill structures since it can increase the water conductivity and thereby leaching. With other construction materials and field conditions, the result may not be the same. Therefore, studies are needed to get a suitable layer thickness for the selected construction material in the field conditions. (Zhongkui, 2016.)

3 Utilization of Municipal Solid Waste Incineration Bottom Ash (MSWI BA) in landfill construction

Municipal solid waste incineration bottom ash (MSWI BA) is the non-combustible part of incinerated waste that are discharged in huge amount from the waste incineration plants. In Finland, there are nine running incinerator plants. Annually, about 300 000 tonnes of bottom ash are generated from these incineration plants. Mainly grate firing technology is used for incineration in most of the plants in Finland. (Suomen eritysjäte oy, 2018.) MSWI BA is a highly heterogeneous material. Thus, in addition to ash, it also contains metal, glass, ceramics and unburnt organic material. (Izquierdo et al., 2001.) Bottom ash (BA) is first treated by removing magnetic and non-magnetic metals. The treated bottom ash contains several minerals, and this can be utilised for suitable earthwork construction. (Suomen erityisjäte oy, 2018.) Bottom ash from the waste incineration plants contain considerable amount of soluble salts and partly soluble constituents, such as metals. Therefore, there are chances that those particles (leaching) can be released in construction site and contaminate the environment. (Puma et al., 2013.) Leaching is the dissipation of a soluble component from a solid phase into a solvent. When the solvent passes through a solid waste, leaching can happen, due to the chemical reaction between solid waste particle and the solvent. (Sabbas et al., 2001.) However, BA can be stabilised with specific treatments such as aging, weathering, washing with water, carbonation, etc. to reduce the mobility of constituents of potential environmental concern. During these processes, several physical and chemical reactions may take place, such as carbonation, hydrolysis, hydration, pH neutralisation, oxidation of metals, etc. MSWI BA is an alkaline material. Typical pH value of a fresh MSWI BA is in between 10 – 12 and the pH reduces below 10 after the stabilising processes. (Saffarzadeh et al., 2011.)

Due to good civil engineering properties of bottom ash and the unavailability of bulk amount of natural soil for landfill construction, it is a great way to use bottom ash as a construction material in landfill (Sormunen, 2017). According to the studies, using the bottom ash in landfill cover structure construction is relatively safe than using it in other construction sites. The reason is, even though the solubility of harmful substances can exceed the limits in some stage after construction, the release of harmful substances only happens in a protected and monitored area for waste. Thus, when the BA is used as construction material, environmental impact due to the released harmful material can be less at landfill sites than in the other construction sites. In addition, using the bottom ash for landfill construction reduces the construction cost, environment pollution and the problems due to soil excavation. (Puma et al., 2013.) Figure 3.1 is the picture of MSWI BA stored in the Ämmässuo landfill.

Figure 3.1 MSWI BA stored in the Ämmässuo landfill (Picture: Hima Jijo)

In 2017, Ämmässuo landfill received over 72000ton of MSWI BA. At Ämmässuo landfill, currently many projects are going on for incorporating MSWI BA in the landfill cover constructions (HSY, 2017a).

This section discusses about the Finnish guidelines for using waste materials in construction, engineering properties and the reactivity of MSWI BA.

3.1 Finnish guidelines for using waste materials in construction

Legislation regarding assessing the suitability of waste materials in civil engineering applications can be different for different countries. (Saveyn et al., 2014). Various kind of leaching tests and procedures are used among different European countries for basic characterization and testing the compliance. (Sormunen, 2017.) In Finland, assessment of the waste-derived aggregates for civil engineering applications are done according to the Government Decree 843/2017. The purpose of this regulation is to promote the recovery of the waste. If the construction material satisfies the conditions referred in decree 843/2017, the earthwork constructions does not need an environmental permit as per the Environmental protection act 527/2014. However, the holder of the recovery waste site shall submit a notification of the activity to the state supervisory authority for the registration in the environmental protection database. Notification includes details regarding the waste, site, construction and holder. Treated bottom ash (slag) from waste incinerator is included under this decree. The use of treated bottom ash after removal of iron and other metals from waste combustion is permitted in roadway, field structures and in the floor structures of industrial and storage buildings. Table 3.1 shows the permitted limit for harmful substances, thickness of the waste layer at earth construction sites and other quality requirements. (Vna 843/2017.)

Table 3.1 Recovered waste: maximum permitted solubility of harmful substances (mg/kg L/S per 10 l/kg), content of harmful substances (mg/kg dry material) and layer thickness at the earth construction site. (Vna 843/2017)

Harmful substance	**Earth construction site**						
	Roadway[1] waste layer thickness ≤ 1.5 m		**Field**[1] waste layer thickness ≤ 1.5 m		**Embankment** waste layer thickness ≤ 5.0 m	**Floor structure of industrial or storage building** waste layer thickness ≤ 1.5 m	**Road constructed of crushed stone and ash**[2] waste layer thickness ≤ 0.2 m
	Covered	**Paved**	**Covered**	**Paved**	**Covered**		
Solubility (mg/kg LS = 10 l/kg)							
Antimony (Sb)	0.7	0.7	0.3	0.7	0.7	0.7	0.7
Arsenic (As)	1	2	0.5	1.5	0.5	2	2
Barium (Ba)	40	100	20	60	20	100	80
Cadmium (Cd)	0.04	0.06	0.04	0.06	0.04	0.06	0.06
Chrome (Cr)	2	10	0.5	5	1	10	5
Copper (Cu)	10	10	2	10	10	10	10
Lead (Pb)	0.5	2	0.5	2	0.5	2	1
Molybdenum (Mo)	1.5	6	0.5	6	1	6	2
Nickel (Ni)	2	2	0.4	1.2	1.2	2	2
Selenium (Se)	1	1	0.4	1	1	1	1
Zinc (Zn)	15	15	4	12	15	15	15
Vanadium (V)	2	3	2	3	2	3	3
Mercury (Hg)	0.03	0.03	0.01	0.03	0.03	0.03	0.03
Chloride (Cl^-)[3]	3 200	11 000	800	2 400	1 800	11 000	4 700
Sulphate (SO_4^{2-})[3]	5 900	18 000	1 200	10 000	3 400	18 000	6 500
Fluoride (F^-)[3]	50	150	10	50	30	150	100
Dissolved organic carbon (DOC)	500	500	500	500	500	500	500
Content (mg/kg dry material)							
Benzene	0.2	0.2	0.02	0.2	0.06	0.02	0.2
TEX[4]	25	25	25	25	25	10	25
Naphthalene	5	5	5	5	5	5	5
PAH compounds[5]	30	30	30	30	30	30	30
Phenolic compounds[6]	10	10	5	10	10	10	10
PCB compounds[7]	1	1	1	1	1	1	1
Petroleum hydrocarbons C10-C40	500	500	500	500	500	300	500

In addition to the permitted limit of harmful substances, quality requirements are applied to the recovery of waste. The waste for recovery should meet the technical and functional requirements for building elements used in earth construction sites. The maximum permitted granular size in treated waste combustion slag is 50mm. The recovery of waste should undergo waste quality management to ensure that the waste is suitable to use in accordance

with the Decree Vna 843/2017. And it includes undertaking the required measures by the party handling the waste. (Vna 843/2017.)

Work safety and environmental impact have to be considered during the storage, handling, and transportation of waste materials. Tests for each waste material using in earthwork construction have to be selected according to the difference in the properties of waste materials from the natural soil. Construction with waste material should be compatible with the other materials used in the construction. (InfraRYL, 2018.)

Finnish legislations are promoting using waste materials in landfill construction works by avoiding tax to those waste materials, which could use in landfill constructions. Otherwise landfilling waste materials are levied a tax of 70euros per ton. (Jäteverolaki 17.12.2012/1126.)

3.2 Engineering properties of MSWI BA

MSWI BA is considered as an aggregate material. Properties of MSWI BA can be different depending upon the particle size, properties of the waste material, burning conditions and the method of incineration. BA is porous in nature. Nowadays, MSWI BA are mainly available in 0-5mm, 5-12mm and 12-50mm grain sizes. The suitability of materials used for earthwork constructions can be ensured in advance by preliminary geotechnical tests. (Suomen Eritysjäte oy, 2018.) Bottom ash used in the Ämmässuo test structure was procured by Vantaan Energia. Properties of the bottom ash available in Ämmässuo was tested at Ramboll Oy for HSY in 2017. Tests were done for determining grain size distribution, water content, coefficient of water permeability, bulk density, dry density, optimum moisture content and maximum dry density of MSWI BA. Mainly the BA with grain sizes 0-4mm, 4-12mm and 12-40mm were tested. Details of the test are included in the next subsections.

Grain size distribution and water content

Grain size analysis were done for three different particle range 0-4mm, 4-12mm and 12-40mm by dry and wet sieve analysis. Table 3.2 represents the test results and figure 3.2 is the grain size distribution curve of different particle size.

Table 3.2 Water content and sieve analysis results(Picture: Ramboll, 2018a)

Particle size	water content w [%]	soil type with respect to particle size	
		By dry sieve analysis	By dry and wet sieve analysis
BA 0-4mm	19	grSa	grSa
BA 4-12mm	8.9	Gr	Gr
BA 12-40mm	6.7	Gr	Gr

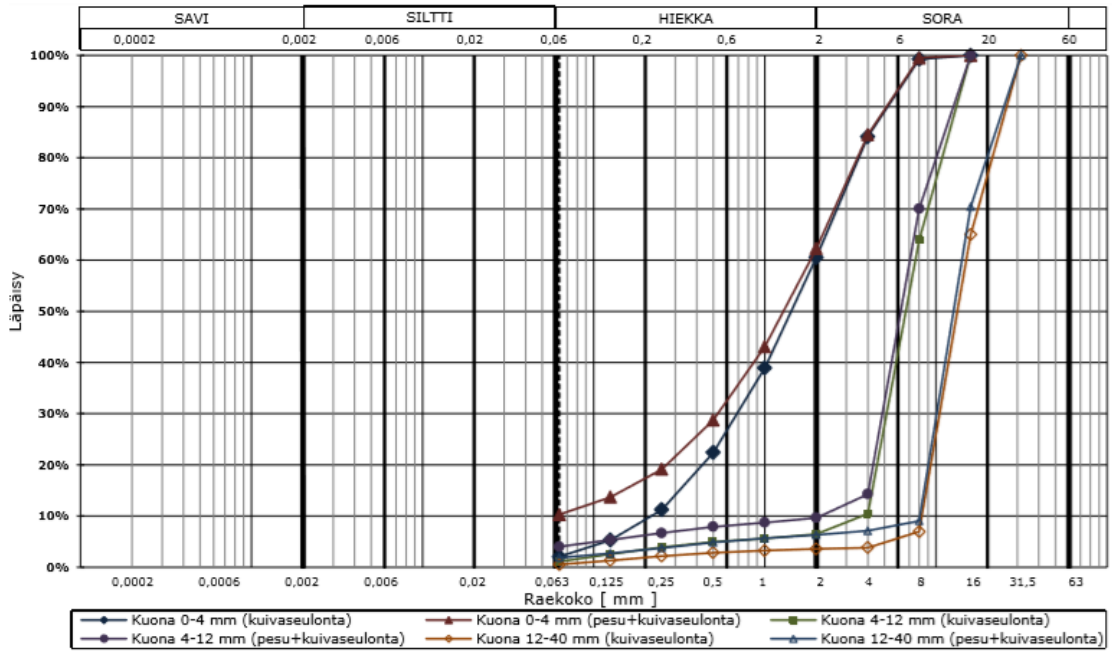


Figure:3.2 Grain size distribution curves of MSWI BA by dry and wet sieve analysis(Picture: Ramboll, 2018a)

According to the test result, 0-4mm size BA sample was in gravel sand range (grSa) and 4-12mm and 12-40mm size BA samples were in the gravel range (Gr). Water content was determined with oven drying method. Moisture content in 0-4mm size BA sample was 19%. Moisture content in 4-12mm and 12-40mm size BA samples were 8.9% and 6.7% respectively. Moisture contnet was higher in 0-4mm than in the 4-12mm and 12-40mm size particles. Grain size distribution for any other BA sample batches other than the above can be different due to the difference in the amounts of fine particles in that particular sample. (*Ramboll, 2018a*.)

Maximum dry density and optimum moisture content

Modified proctor test was used to determine the optimum moisture content and dry density. Figure 3.3 shows the modified proctor test result (graphs). The results for 0-4mm shows more logical than the other two samples. Table 3.3 shows the maximum dry density and the optimum moisture content of the samples. During proctor test, the BA particles might have crushed and fined. Thus, the results could have been affected with crushing and fining. In the work sites, for achieving more compaction (>90%), big particles are used to crush. Thus, a similar kind of results can be expected. (*Ramboll, 2018a*.)

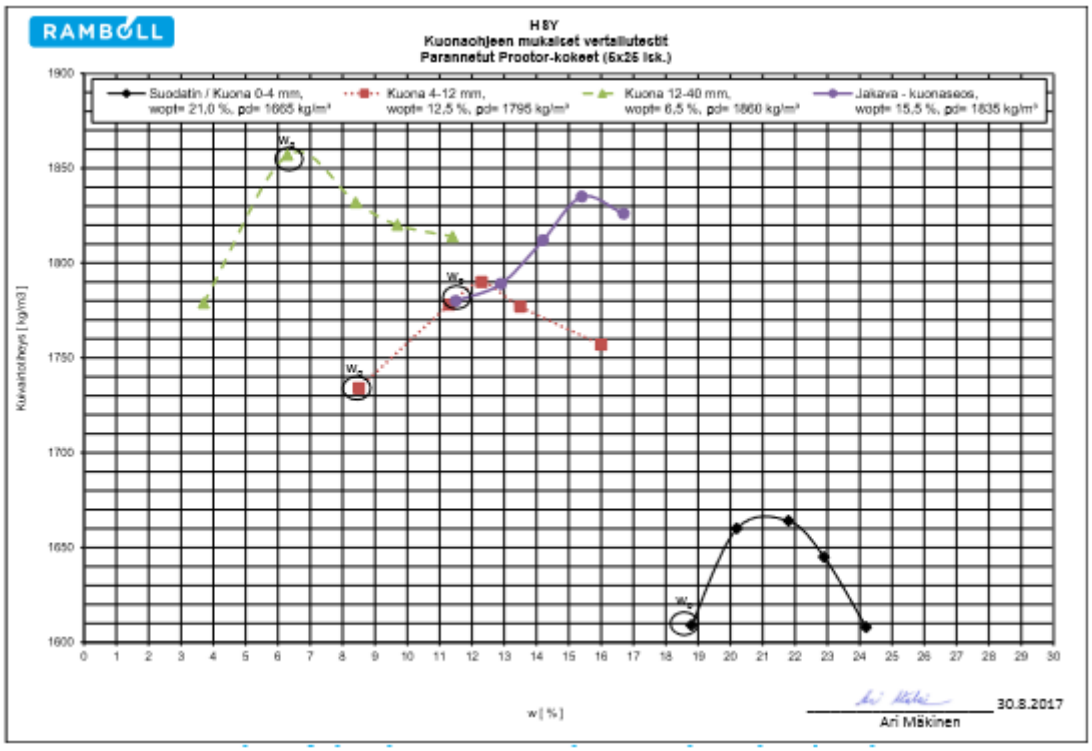


Figure 3.3 Modified Proctor test results (Ramboll, 2018a)

Table 3.3 Modified Proctor test results (Ramboll, 2018a)

Particle size	Maximum Dry density	Optimum moisture content
BA 0-4mm	1665 kg/m^3	21.0%
BA 4-12mm	1795 kg/m^3	12.5%
BA 12-40mm	1860 kg/m^3	6.5%

Water permeability

Table 3.4 shows the water permeability test results done in Ramboll Oy. Test was done with flexible wall cells. The result shows that the water permeability is highly dependent on the degree of compaction and the particle size. For BA 0-4mm, even for 5% of variation in the degree of compaction, coefficient of water permeability changes by 100 times.*(Ramboll, 2018a..)*

Table 3.4 Coefficient of water permeability of MSWI BA(Table: Ramboll, 2018a)

particle size	Degree of compaction D [%]	Coefficient of water permeability k[m/s]
BA 0-4mm	92	5.7x10^{-8}
	87	5.0x10^{-6}
BA 4-12mm	95	1.5x10^{-6}
	90	3.8 x 10^{-5}

According to earlier other studies, the reported water permeability values have a large variation, almost five orders of magnitude, ranging from 10^{-8} to 10^{-5} m/s (Sormunen, 2017; HSY, 2018; Leppänen 2018). The results are very sensitive to the changes in moisture content, grading of the material and degree of compaction. However, MSWI BA isrecognized as a material with high drainage characteristics. (Sormunen, 2017.)

Landfill impermeable layer requires a very low permeability $k< 1 \times 10^{-9}$ m/s for permanent cover and the recommended value for temporary cover is $k< 1 \times 10^{-8}$ m/s (RTS, 2018; SYKE, 2008). Achieving 92% compaction may be difficult in construction sites. Thus, additives can be added with bottom ash to satisfy the permeability criteria, if the bottom ash uses for the impermeable layer construction. By adding low permeability materials such as kaolinite, bentonite, Trisoplast, coal fly ash, Portland cement, bitumen, etc., required permeability can be achieved. (Sormunen, 2017; SYKE, 2008; Meggyes et al., 1998)

Capillary rise, Thermal conductivity and Frost heave

According to the tests by Ramboll, capillary rise for BA is higher than the results given in the bottom ash instruction by Suomen erityisjäte Oy. This may be due to the high degree of compaction done during the test by Ramboll. Therfore, the layer thickness for intended use should be selected considering the correspondant capillary rise. Table 3.5 shows the capillary rise results of BA 0-4mm and 4-12mm. (*Ramboll, 2018a*.)

Table 3.5 Height of capillary rise of MSWI BA (Ramboll, 2018a)

particle size	Dry density [kg/m^3]/ (Degree of compaction D[%])	Capillary rise[mm] 1/2/3month
BA 0-4mm	1292/(78)	380/500/540
	1397/(84)	390/500/560
BA 4-12mm	1148/(64)	160/220/280
	1408/(78)	270/330/420

Table 3.6 Thermal conductivity of MSWI BA (Ramboll, 2018a)

particle size	Degree of compaction D[%]	soil condition	Thermal conductivity λ[W/mK]
BA 0-4mm	92	Thawing	0.7
		Freezing	0.88
BA 4-12mm	95	Thawing	0.47
		Freezing	0.58

Table 3.6 shows the thermal conductivity and table 3.7 shows the frost heave coefficient values of BA 0-4mm and 4-12mm in two different degree of compaction. (*Ramboll, 2018a*.)

Table 3.7 Frost heave of MSWI BA (Ramboll, 2018a)

particle size	Degree of compaction D[%]	Frost heave (24h / 96h/144h) [mm]	Frost heave coefficient Spo (12-24h/23-25h/24-72h) [mm2/KH]	Frost susceptibility
BA 0-4mm	92	3.2 / 5.6 / 5.8	1.9 / 1.3 / 0.7	Frost susceptible/slightly frost susceptible
BA 4-12mm	95	1.4 / 2.8 / 3.2	1.0 / 0.8 / 0.5	Frost susceptible/slightly frost susceptible

According to the Table 3.7, frost heave coefficient of the first two parts of the test results (12-24h and 23-25h) are high. However, in the last part 24-72h, the frost heave coefficient reduced and it was in the slightly frost susceptible range. The material having frost heave coefficient between 0.18 – 0.72 is slightly frost susceptible and 0.72 -3.6 is frost susceptible. (*Ramboll, 2018a*.)

3.3 Reactivity of MSWI bottom ash with landfill gas

Early studies state that MSWI BA can use for removing carbon dioxide (CO_2) and hydrogen sulphide (H_2S) from the landfill gas and thereby upgrade landfill gas by enriching the methane. This is because CO_2 and H_2S can react with MSWI BA. Since methane is an inert gas, no reactions take place between methane and BA. (Ducom et al., 2008.)

The CO_2 removal happens due to the carbonation mechanism. It happens in several steps as explained in the equation 7 to 10.

Hydration of CaO: $CaO + H_2O = Ca(OH)_2$, ΔH = -65 kJ/mol (7)
Partial dissolution of portlandite: $Ca(OH)_2 = Ca^{+2} + 2\ OH^-$ (8)
Carbonation: step 1) $CO_2 + H_2O = H_2CO_3$ (9)
step 2) $H_2CO_3 + Ca^{2+} + 2\ OH^{2-} = CaCO_3 + 2\ H_2O$ (10)

As explained in the above equations, first the CaO in the MSWI BA is hydrated to form portlandite $Ca(OH)_2$. Portlandite $Ca(OH)_2$ dissolve partially in the water. Next, when the CO_2 pass through the bottom ash, CO_2 dissolves into water. When this dissolved CO_2 comes in contact with the partially dissolved portlandite, they form solid calcite (CaCO3). These processes thus remove the CO_2 from the landfill gas (Rendek et al., 2005.; Lombardi et al., 2012.)

Carbonation depends upon several factors such as pressure of the CO_2, sieving, moisture content and pH of BA. When CO_2 pressure increases, more CO_2 dissolves into water and more reactions happens. With low gas pressure, it may take more time for the carbonation. When the moisture content is low, dissolved portlandite and CO_2 will be less and thus the reaction rate will be low. On the other hand, when the moisture content is high, CO_2 and BA particles can not come into contact with each other and the reaction rate will be low. According to Rendek et al. 2005, 15% is the optimum moisture content for the carbonation.

Sieving and grain size of BA also affect the carbonation. By sieving, glass, ceramics and other unreacted particles can be removed from the bottom ash. Thus, the finer particles of BA have higher Ca content, which increases the reaction rate. (Rendek et al., 2005.) Ducom et al. (2008) also noticed that the bottom ash of grain size 0-2mm shows more carbon dioxide uptake than 0-4mm or 0-8mm. Furthermore, bottom ash with high pH have high reactivity. High pH in the bottom ash is due to the presence of dissolved portlandite. Dissolved portlandite can react easily with the CO_2. Carbonation process usually decreases pH of the BA. (Rendek et al., 2005.)

The amount of CO_2 uptake can be calculated by mass analysis (Mostbauer et. al., 2007) and calcimetry analysis (Lombardi et al., 2012) of the BA. In the mass analysis, mass of unreacted BA (before the carbonation) and reacted BA (after the carbonation) is weighed, and the CO_2 uptake is calculated from the weight difference (Mostbauer et. al., 2007). Calcimetry method is usually used to determine the calcium carbonate content of the BA. Difference in the mass percentage of $CaCO_3$ in the BA (before and after the BA carbonation) determines the CO_2 uptake. (Lombardi et al., 2012.)

Many researchers have studied the CO_2 uptake of BA and found that CO_2 uptake is different for different types of BA samples. The CO_2 uptake of MSWI BA also varies considerably with the test conditions such as difference in the CO_2 concentration in the gas sample, test duration and the differences in the properties of BA used. (Lombardi & Carnevale, 2016.) Table 3.8 shows the CO_2 uptake of BA in different studies.

Table 3.8 CO_2 uptake in kg by 1ton bottom ash in different studies

Material	**CO_2 uptake kg/1t BA**	**References**
MSWI BA from central Italy	21 – 37 kg	Lombardi et al., 2012
MSWI BA from Lyon, France	11 kg	Ducom et al., 2008
MSWI BA from central Italy	24 kg	Lombardi & Carnevale, 2016
MSWI BA from Vienna, Austria	15.5 – 39.0 kg	Mostbauer et al., 2007
MSWI BA from Italy	10.5 -11.3 kg	Olivieri et al., 2011
MSWI BA from Germany and Austria	39 kg	Olivieri et al., 2011
Upgraded MSWI BA from Finland	9 – 17.5 kg	Mostbauer, 2014

Hydrogen sulphide (H_2S) in an aqueous medium can be in ionic form and thus can react with the Calcium hydroxide $Ca(OH)_2$ in the bottom ash. Since the sulphide ion is in the ionic form, H_2S can also react with various metal cations and produce sulphides, such as iron sulphide, lead sulphide, zinc sulphide, etc. These reactions enable the reduction of the sulphide from the landfill gas. In the Mostbauer studies on BA samples collected from different countries, H_2S uptakes of 0.1 to 3.0 kg H_2S /t BA were noticed in the various samples. Results from the Mostbauer studies is described in the Table 3.9.

Table 3.9 Cumulative hydrogen sulphide observed kgH_2S/t BA (Table: Mostbauer, 2014)

Material	**Input gas flow rate per t of ash[m^3/t*h]**	**Cumulative H2S uptake observed [kgH_2S/t BA]**	**References**
Upgraded MSWI bottom ash from Freiburg, Germany	7.9	0.91	Unpublished expertise, 2009
MSWI bottom ash from Arezzo, Italy	2.4	0.037	www.upgas.eu, 2012
MSWI bottom ash from Lyon, France	63 – 70	3.0	Ducom ea., 2009
Upgraded MSWI bottom ash from Finland, sample 1	5.0 / 10.0	0.55/0.68	Mostbauer, 2014

Another study by Ducom et al. 2008 also showed the H_2S uptakes of 3kg H_2S /t BA. According to Ducom et al. 2008, the reaction time between H_2S and bottom ash has a great role in the reaction rate. For instance, in his study, it was noted that when the allowed reaction duration was 12second, the reaction between H_2S and BA was very low. On the other hand, when the reaction duration was 23second, more reactions occurred, and it seems to be a good duration for the reaction to happen. Moisture content in the BA can also influence the H_2S reaction rate. In the dry BA, H_2S reaction rate was very low. (Ducom et al., 2008.)

Furthermore, in the Ducam's studies it was noticed that, in the BA, CO_2 reaction happens faster than H_2S reaction. However, even after the carbonation, the H_2S can react with the BA. BA also remove other components of the landfill gas such as methyl mercaptan and dimethyl sulphide. For instance, for a ton of BA, uptake of methyl mercaptan is 0.044kg and uptake of dimethyl sulphide is 0.086 kg. Thus, the bottom ash in the landfill cover can help to remove CO_2, H_2S, methyl mercaptan and dimethyl sulphide and thereby reduces the harm caused due to the emission of these gases. Removal of CO_2, H_2S, methyl mercaptan and dimethyl sulphide can also enrich the landfill gas with methane, thereby enhancing the thermal energy utilization efficiency of the landfill gas. (Ducom et al.2008).

4 Ämmässuo test structures

Ämmässuo waste treatment centre have participated in the studies on incorporating the municipal solid waste incineration bottom ash (MSWI BA) in the landfill construction. Accordingly, two temporary test cover structures were constructed in Ämmässuo landfill in 2015 and 2017. The third temporary test cover structure was under construction in autumn 2018, during the period of this research study. MSWI BA was used as construction material in all the three test structures.

Ämmässuo landfill is one of the largest landfills in the Nordic countries which is situated in the Espoo and Kirkkonummi cities. Ämmässuo landfill is under the Helsinki Region Environment Services Authority (HSY). HSY is responsible for the constructions, and operations of the Ämmässuo waste treatment centre. Ämmässuo waste treatment centre is handling waste management services in the Helsinki metropolitan area. Landfill in the Ämmässuo started operation in 1987. Ämmässuo waste treatment centre is 200 ha wide area. 52 ha of old landfill area was closed in 2007. Out of 12.4 ha new landfill area, only 6 ha is in the active use. (HSY, 2017a.) Figure 4.1 shows the aerial view of Ämmässuo landfill.

Figure 4.1 Ämmässuo landfill, aerial view (HSY, 2018a)

Waste treatment facilities of HSY include waste reception, pre-treated landfill waste, bio-waste treatment plant, treatment and recovery of contaminated soil, ashes and slags, disposal of wastewater and waste landfill collection and recovery. Ämmässuo waste treatment centre received 72191 ton of MSWI BA in the year 2017. Majority of the received MSWI BA (72188 ton) was from Vantaan energia. The all three test cover structures in Ämmässuo fill are situated in the new landfill area (S1). (HSY, 2017a.) Figure 4.2 shows the map of S1 landfill area and the approximate location of the two test structures. During this research study, gas measurements were taken from these test structures to study the gas permeability of the test structures.

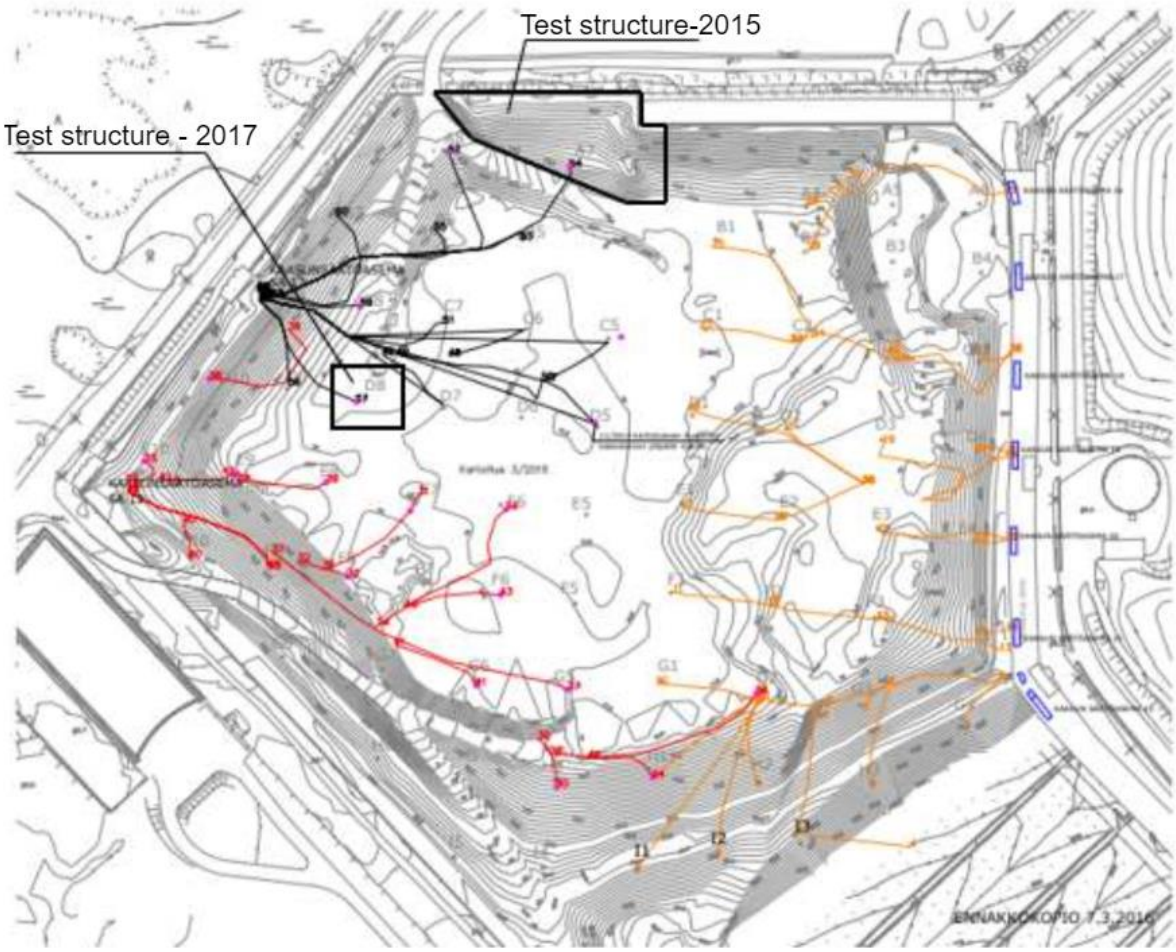


Figure 4.2 Map of Ämmässuo S1 area (Ramboll, 2015)

4.1 Temporary test cover structure in 2015

For studying the effectiveness and suitability of MSWI BA as a construction material for the landfill cover structure, the first cover structure was constructed in the Ämmässuo land fill during spring 2015. This test cover structure was 0.4 ha site and was situated in a sloped area. In this test structure, a 500mm thick impermeable layer was constructed above the disposed waste. A mixture of 0-2mm grain size MSWI BA and 3% of polymer modified sodium bentonite was used as construction material for the impermeable layer. Constructed impermeable layer was then covered with 1.5mm thick LLDPE membrane and a protective geotextile. Finally, the whole structure was covered with 500mm thick drainage layer using crushed rocks. No top cover layer or vegetation layer was built over this structure. (Leppänen et al., 2018.) Figure 4.3 presents the test cover structure built in 2015. The test cover structure is located around the gas collection well A7 in S1 area.

Figure 4.3 Picture of the Temporary test cover structure built in 2015

To evaluate the gas emission through the test cover structure, three flux boxes were installed on different layers of the cover structure. The first box was installed above the LLDPE membrane and the second box was installed above the impermeable layer. Third chamber was installed above waste layer outside the test structure area. Figure 4.4 represents how the flux boxes are positioned in the cover structure.

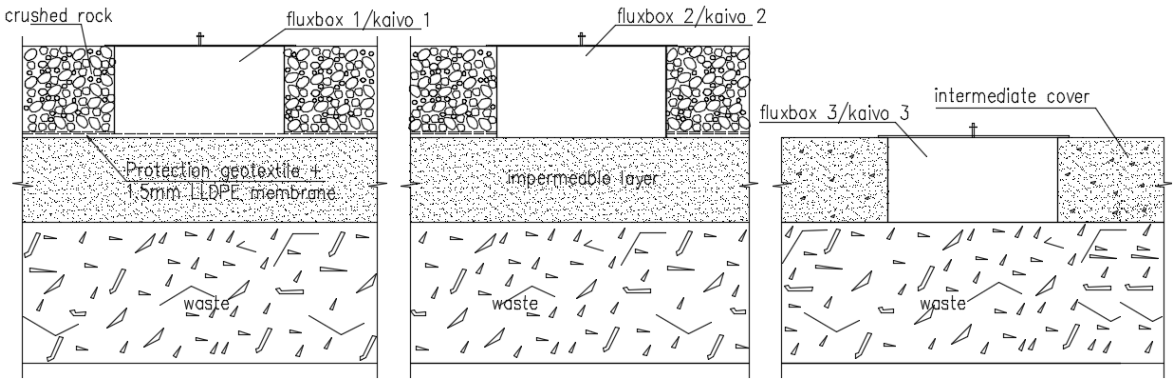


Figure 4.4 schematic sectional drawing of the flux boxes positions in the 2015 test structure (Figure: Hima Jijo)

As illustrated in the Figure 4.4, flux boxes were opened from the bottom and were closed at the top with a gas tight lid. Outlet gas taps were installed above each flux box for measuring the gas composition from different layers.

Preliminary tests were done by Tampere University for assessing the technical suitability of the MSWI BA in the impermeable layer of the landfill cover structure. Based on the environmental permit of Ämmässuo waste treatment centre, the target permeability value for the cover structure was set at $k \leq 1 \times 10^{-9}$ m/s. The permeability of a well compacted MSWI BA is typically around 1×10^{-7} m/s. Thus, in order to achieve the required permeability, bentonite or similar kind of additives were required. MSWI BA has a high pH value of 10 – 12 and the grains of BA are porous. Accordingly, for getting the required water permeability, pH value and the grain size of MSWI BA determine the quantity and the type of bentonite for mixing with BA. MSWI BA also contains a high concentration of diluting chlorides, sulphides and calcium, which can decrease the swelling properties of the bentonite. Consequently, polymer modified sodium bentonite was chosen for the construction of the test structure. Polymer treated sodium bentonite contains additional superabsorbent polymers, which have a very high resistivity to aggressive leakages. This can highly enhance performance and self-healing capability of the bentonite. (Leppänen, 2018.)

Different bentonite types with different proportions were tested. However, the required water permeability $k \leq 1 \times 10^{-9}$ m/s was achieved only with polymer modified sodium bentonite. Coefficient of water permeability measured for 0-2mm MSWI BA and 3% polymer modified sodium bentonite (used in the 2015 structure) was 1.1×10^{-10} m/s, which was lower than the required value. Results of water permeability tests of different mixtures are included in the Appendix 1. During construction, it was noticed that water content had a great influence in the compaction of the MSWI BA- bentonite mixture.

Fine size 0 - 2mm BA often contains more contaminants than bigger grain size BA. Studies by Leppänen, 2018 showed that the use of fine size 0-2mm BA in the construction of the landfill cover structure is promising since the use of 0 - 2mm BA is limited in other construction. However, the long-term consequences of the modified bentonite mixtures with the BA was not available. (Leppänen, 2018.)

This structure was opened for inspection in 2017. No crack was found in the cover structure during the examination. However, some black and white dots were spotted, and they were assumed to be gas escaping spots. (Leppänen, 2017.)

During the inspection, gas methane emission measurements were conducted over the waste layer and the impermeable layer with a DP-IR methane detector. There was significant difference in the methane concentration from the waste layer and the impermeable layer. Methane concentration from the waste layer measured 1000s ppm, but only a 15-25ppm concentration of methane measured from the top of impermeable layer. This explains the test structure had a low gas permeability and the impermeable layer was acting as a barrier against the landfill gas emission. (Leppänen, 2017.)

Troxler measurements and the sand replacement method was done at the site for measuring the water content and density of the test structure. Samples were collected from the test structure for analysing the pH, swelling index, water content, solubility, grain size, water permeability, etc. Figure 4.5 shows the pH and electrical conductivity of the sample. Other analysis results are included in the Appendix 2. (Leppänen, 2017.)

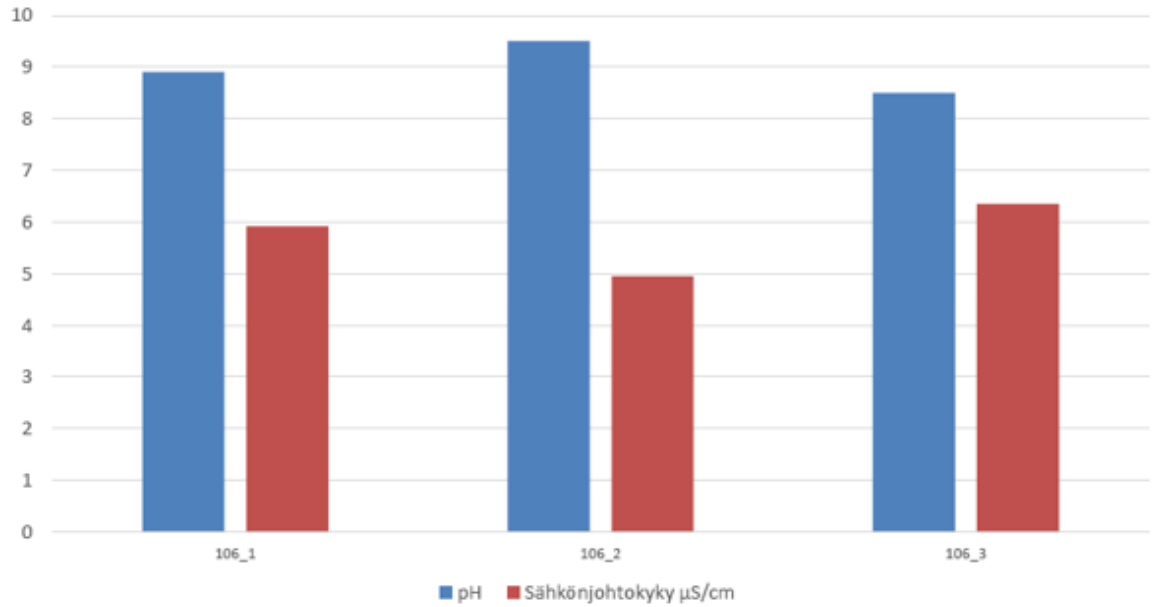


Figure 4.5 pH and electrical conductivity of samples collected from the cover structure in 2015 (Leppänen, 2017)

Water content in the collected samples was in the range 27.5 – 33.2%. Measured water content during the construction in 2015 was in the range 27 – 30%. Average swelling index of the collected sample was 3ml/2g. On the other hand, swelling index of bentonite alone is 26ml/2g. Average solubility of the BA-bentonite mixture in the hydrochloric acid was 47.93% and the solubility of BA alone was 46.4%. Thus, there was no significant difference noticed between the solubility of these two materials in the hydrochloric acid. (Leppänen, 2017.). Photographs of the 2015 - test cover structure during the inspection in 2017 is in the Figure 4.6.

Figure 4.6 Photographs of the 2015 - test cover structure during the inspection in 2017 (Leppänen, 2017)

4.2 Temporary test cover structure in 2017

This temporary test cover structure was constructed in 2017 and it was designed as a reactive cover. The objective of this test structure was to study the gas permeability of the structure made with MSWI BA and to study the effectiveness of bottom ash reactivity with landfill gas components. Reactivity of the bottom ash with CO_2 and H_2S are well known from the earlier studies. Bottom ash is used for removing CO_2 and H_2S and thus upgrading the process of landfill gas. In the Hakkarainen, 2013 study, bottom ash was used in landfill cover construction for reducing the landfill gas components. This study was done in Kujala landfill during 2012-2013. In the Hakkarainen's study, it was observed from the gas measurement analysis that CO_2 concentration was considerably low above the reactive layer. Assumption was, that CO_2 might have removed due to the reaction between the bottom ash and CO_2. This 2017- structure was situated around the D8 gas collection well in S1 landfill area. The built structure was on the top part of the landfill hill. Area of the structure was 8m x 8m. Construction works of this test cover structure was done during 2.10.2017 – 18.10.2017. Figure 4.7 in the next page represents the sectional view of this test structure.

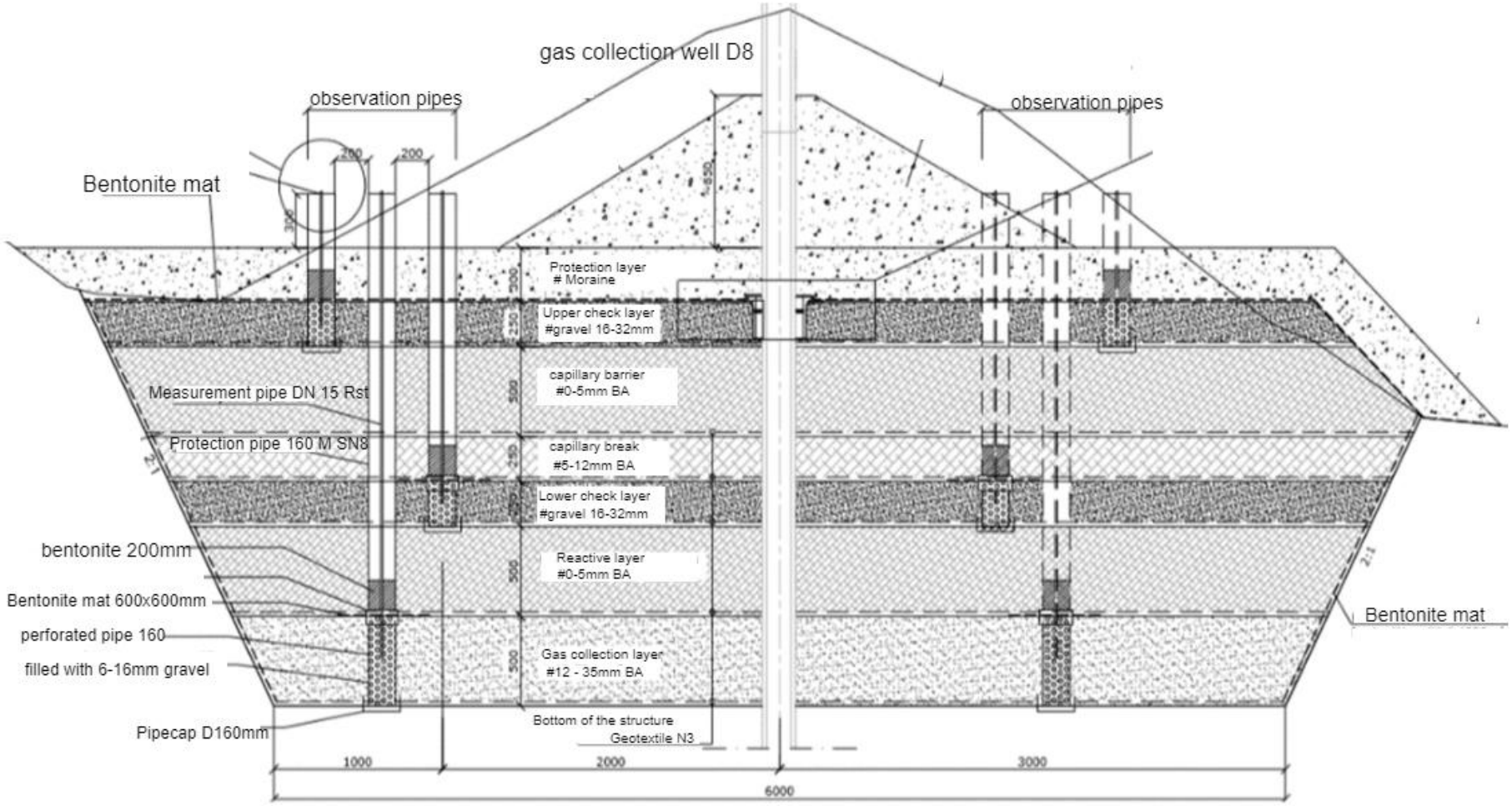


Figure 4.7 Sectional view of 2017 - test structure (Ramboll, 2017)

The boundary of this test structure was covered with bentonite mat for preventing the lateral gas emission. The test structure consists of many layers. A gas collection layer (GCL) was constructed above the waste layer with 12 – 35mm bottom ash. Then a reactive layer with bottom ash of 0-5mm grain size was constructed above the gas drainage layer. Objective of the reactive layer was to remove the landfill gas components using the reactive property of MSWI BA. There was a lower check layer (LCL) above the impermeable layer made with crushed rock of the size 16-32mm. Purpose of the lower check layer was to check the gas concentration above the reactive layer. Observation pipes were installed to this check layer for taking gas measurements. Other layers above the lower check layer were drainage/capillary break layer with 5-12mm BA, a capillary insulation layer with 0-5mm BA and an upper check layer (UCL) with crushed rock 16-32mm. A bentonite mat was used above the upper check layer to cover the structure. Then a top layer with moraine was made above the bentonite mat to protect the bentonite mat from any damages. Geotextiles were attached between each layer to prevent the mixing of different layer materials. Thickness of each layer is highlighted in the schematic Figure 4.7. (Ramboll, 2017.)

Four sets of observation pipes were installed in the test structure around D8 collection well. Each set consists of three observation pipes. Top part of the observation pipe was above the ground level and the bottom part was under the ground level. As shown in the figure 4.7, in each set, the observation pipe near the D8 gas collection well was attached to the lower check layer. Middle observation pipe in the set was attached to the gas drainage layer and the third observation pipe was installed at the upper check layer. (Ramboll, 2017.) Figure 4.8 is the picture of observation pipes from the test structure.

Figure 4.8 Observation pipes and D8 collection pipe from the 2017 test structure (figure: Hima Jijo)

A tap was installed at the top part of each observation pipe for taking gas measurements. The bottom part of the observation pipe was perforated, so that gas can easily pass into the tube for measurement. Above the perforated section, the pipe is sealed with bentonite slurry and the leakage around the pipes are also prevented with bentonite mat. Pictures of this test structure during construction is included in Appendix 3.

5 Gas measurements

For studying the gas permeability of the temporary cover structures made with MSWI BA, gas measurements were carried out for 2015 and 2017 test structures during April - August 2018. Gas measurements from 2017 test structure were taken during 12.4.2018 – 6.8.2018. Gas measurements from 2015 test structure were done during 19.04.2018 – 6.8.2018.

Gas permeability of the test structure was studied by analysing the gas measurements from the test structures. Gas measurements included measurement of gas concentration in the structural layers of the test structures and surface emissions. Weather data was also used to understand the variation in the gas concentration with change in the weather conditions. This section describes gas measurement instruments, used gas measurement methods and the weather details during gas measurements.

5.1 Gas measurements from the structural layers

For understanding the concentration of gas in structural layers of 2015 and 2017 test structures, gas measurements were carried out using a gas analyser. In 2015 test structure, gas measurements were done from the flux boxes. Figure 5.1 shows the picture of flux box in the 2015 test structure.

Figure 5.1 Flux box in the 2015 structures (Figure: Hima Jijo)

In 2017 test structure, gas measurements were taken from the four sets of observation pipes in the different layers of test structure. Figure 5.2 shows the picture of observation pipe in the test structure.

Figure 5.2 Observation pipe in the 2017 structure (Figure: Hima Jijo)

Gas composition of D8 collection pipe was measured from the gas collection centre SA13 in the Ämmässuo landfill using the gas analyser. Landfill gas flow through D8 collection pipe was measured with a flow measuring meter.

5.2 Surface methane emission measurement

For understanding the emission of gas from the surface of 2017 test structure, surface methane emission measurement was done on 27.8.2018 with a methane detector. Originally, this measurement was planned to be done in the beginning of the field measurements. Unfortunately, the DP-IR instrument was in maintenance and the measurement was postponed to August.

Methane gas emission was measured from the top, slope of the 2017 cover structure and around the observation pipes. Surface methane emission measurements had been made from 2015 test structure already in 2017. While data was available, surface methane emission measurements were not redone.

5.3 Instruments used for gas measurements

GA5000 gas analyser was used for measuring gas composition from the observation pipes and flux boxes. In addition to this, TSI VELOCICALC multifunction ventilation meter was used to measure the gas flow from the D8 gas collection pipe in the gas collection centre SA13. GA5000 gas analyser is designed to monitor the landfill gas extraction systems. Thus, GA5000 gas analyser measure the concentration of gas components in percentage by volume. The gas analyser measures methane, carbon dioxide, oxygen in percentage (%), hydrogen sulphide in parts per million (ppm) and barometric pressure in millibars (mb). For taking the measurements, an inline water trapping tubing and a gas analyser managing software also used with the GA5000 gas analyser.

When the gas tap of the observation pipe is opened, gas enters into the gas analyser through the inline tubing connected to the observation pipe. Gas analyser records the components in the gas and save the data. Readings from each observation pipe were saved under a specific name in the gas analyser. Saved data from the gas analyser can be transferred into the

computer for further analysis using the gas analyser managing software. (GA5000 operating manual.). Figure 5.3 is the picture of GA5000 Gas analyser and TSI multifunction ventilation meter.

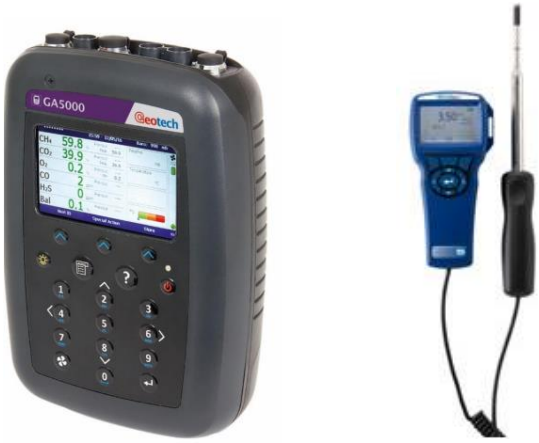


Figure 5.3 GA5000 Gas analyser (GA5000 operating manual) and TSI multifunction ventilation meter

Detecto Pak-Infrared (DP-IR™) instrument was used for the surface methane emission measurements. DP-IR instrument is mainly used for leak survey and it can detect methane gas in an accuracy of 1ppm. The measurement range of the instrument is 1-100,000ppm and 1-100%. DP-IR instrument works by utilizing the Infrared Controlled Interference. The main parts of the instrument are DP-IR instrument and a survey probe. Survey probe helps taking measurements from the leaking points. (DP-IR user's manual Heath Consultants, DP-IR manual, 2007.) Figure 5.4 is DP-IR instrument and the survey probe.

Figure 5.4 DP-IR instrument, survey probe (Picture: DP-IR manual)

5.3 Weather data

For understanding the changes in gas composition with weather, weather data during April to August 2018 was collected from Ämmässuo weather station. Weather data such as atmospheric pressure, temperature, rainfall was used for analysing the gas measurement results. Atmospheric pressure was also collected from gas analyser during the gas measurement time.

6 Measurement data and results

This section discusses the weather data during gas measurements, gas measurement and surface methane emission measurement results from the 2015 and 2017 test structures.

6.1 Weather data during gas measurements

Weather data measured with the gas analyser during the gas measurement is presented in this section. Atmospheric pressure collected from the Ämmässuo weather station is also used for comparison. There was no considerable difference between the gas pressure from gas analyser and Ämmässuo weather station. Figure 6.1 shows the mean atmospheric pressure measured with gas analyser during the gas measurement.

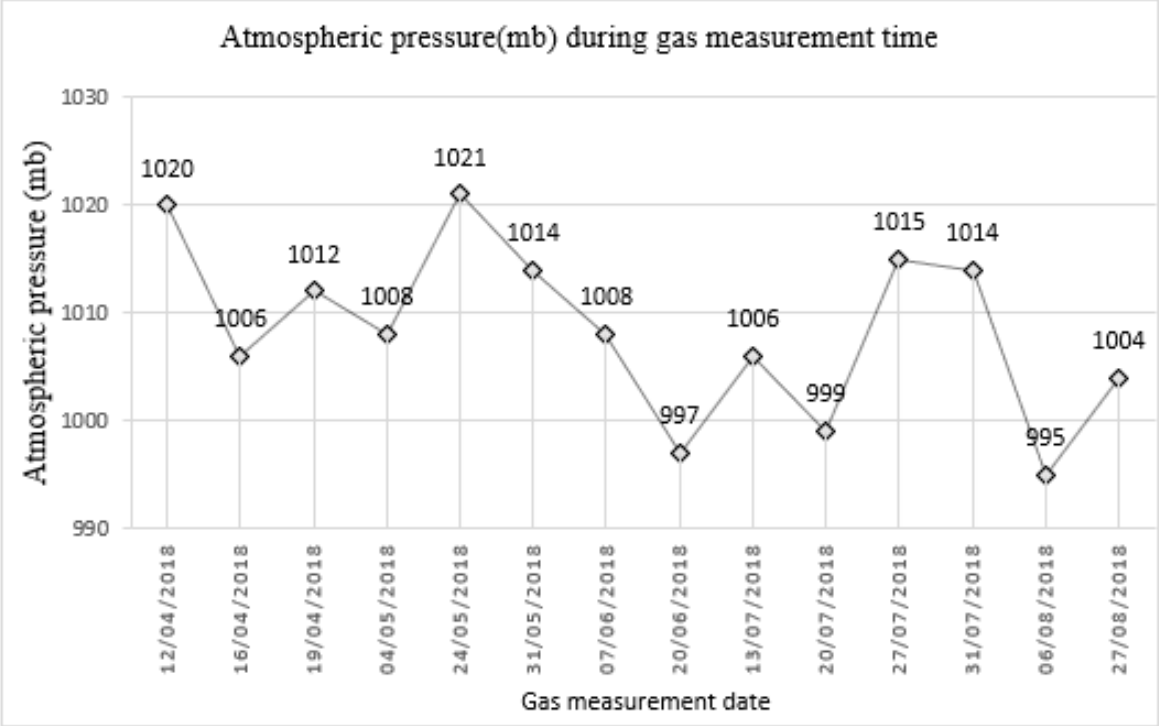


Figure 6.1 Atmospheric pressure (mb) during gas measurement

Atmospheric pressure varied from 995mb to 1021mb during gas measurement period. The lowest atmospheric pressure 995mb was measured on 6.8.2018 and the highest atmospheric pressure 1021mb was measured on 24.05.2018. Details of atmospheric pressure, temperature and rainwater precipitation in each month during the gas measurement period is presented in Appendix 4. More rainfall was recorded in the month of August. There was rainfall during the last three days before surface methane emission measurement. Thus, the ground was wet during measurements. Temperature was low during April and the average daily temperature increased from May onwards. The maximum temperature during the gas measurement period was in July. There was no snow above the test structures during the whole gas measurement period.

6.2 Gas measurement result from the 2015 test structure

In the 2015 test structure, gas measurements were taken above the waste layer, impermeable layer and LLDPE membrane using the flux boxes 1, 2 and 3 during the period 19.04.2018 – 06.08.2018. Concentration of methane, carbon dioxide, oxygen and hydrogen sulphide in each flux box was measured during each measurement. Concentration of methane, carbon dioxide and oxygen are given in percentage (%) by volume and concentration of hydrogen sulphide is given in parts per million(ppm). All gas measurement data of 2015 test structure is included in Appendix 5

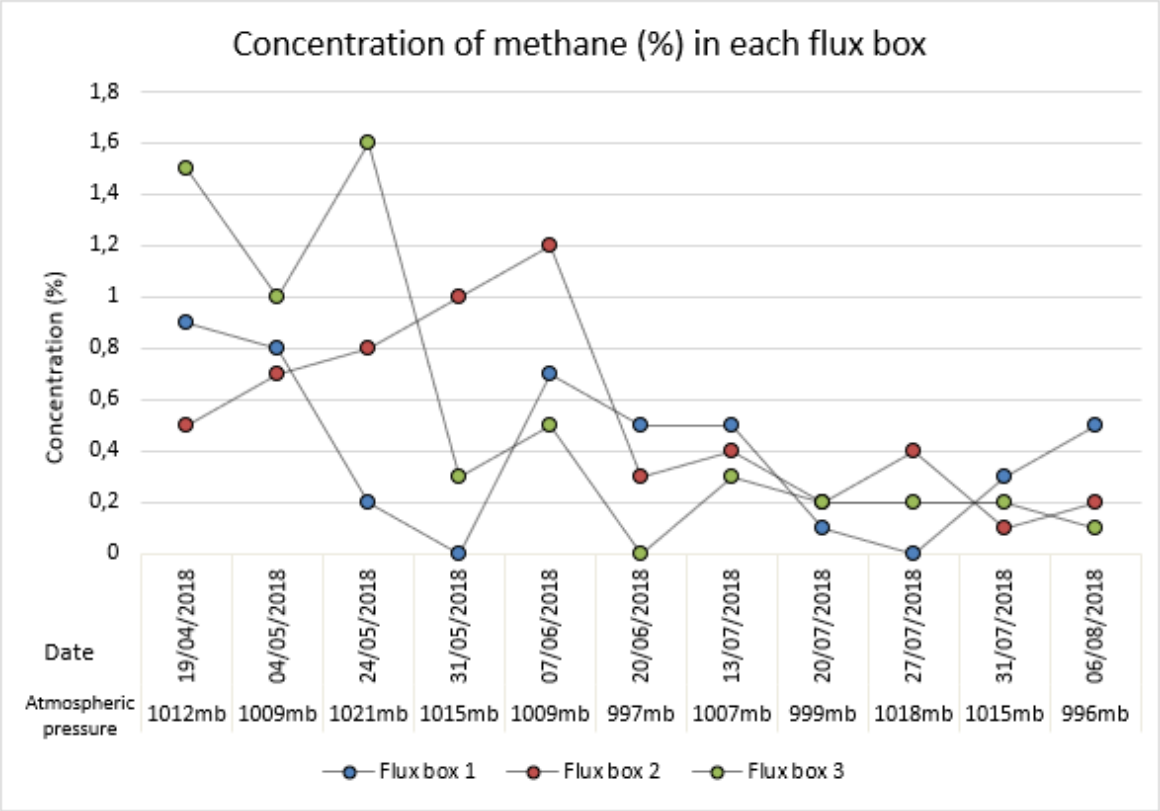


Figure 6.2 Concentration of methane (%) in each flux box during gas measurement

Figure 6.2 shows the measurement details of methane. As described in the figure 6.2, measured concentration of methane was very low in all layers compared to the concentration of methane in typical landfill gas. Typical methane concentration in landfill gas is between 45 – 60%. Maximum concentration of methane was 1.6% above the waste layer (flux box3). Concentration of methane was not varied significantly in flux boxes and only varied between 0 - 1.6% above waste layer. Concentration of methane above impermeable layer (flux box2) and LLDPE membrane (flux box1) was between 0 – 0.9% and 0.1 – 1.0% respectively.

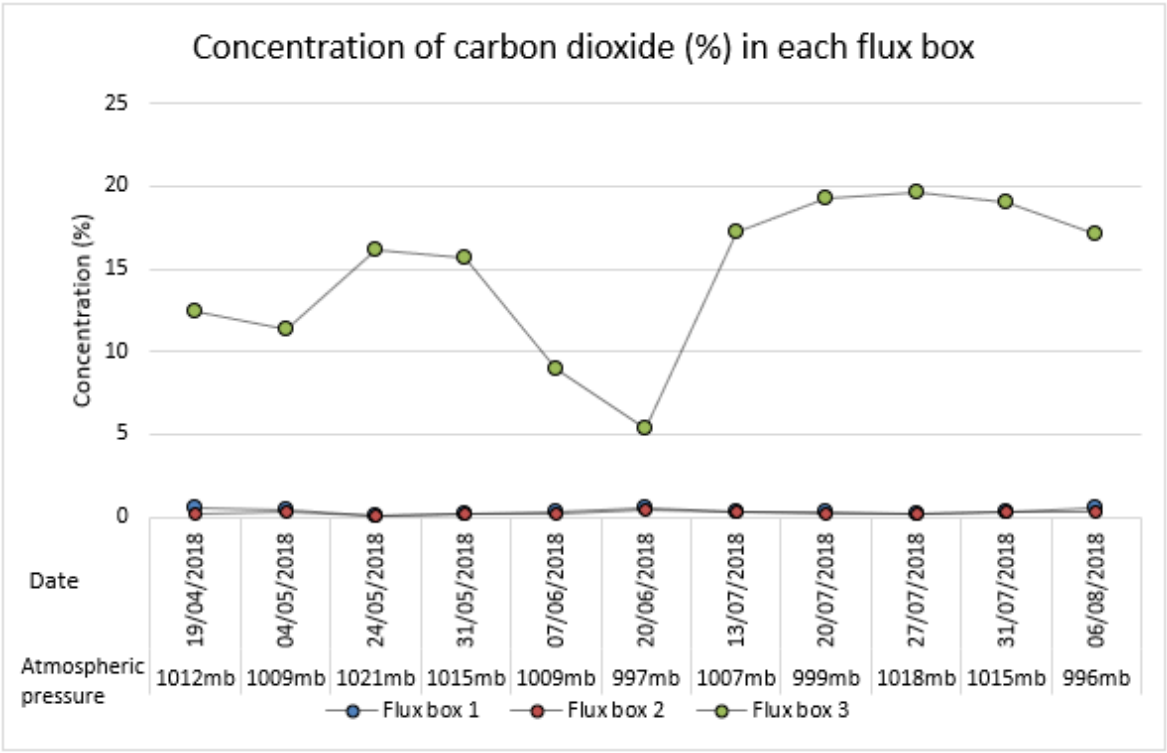


Figure 6.3 Concentration of carbon dioxide (%) in each flux box during gas measurement

Figure 6.3 shows the measurement details of the carbon dioxide. As described in the figure 6.3, concentration of carbon dioxide was considerably lower above the impermeable layer (flux box2) and LLDPE membrane (flux box1) than above the waste layer (flux box3). The value was between 5.3% - 19.6% above the waste layer. Carbon dioxide concentration above the impermeable layer was between 0-0.6%. Carbon dioxide concentration above LLDPE membrane was between 0.1-0.4%. Typical carbon dioxide concentration of landfill gas is between 40 - 60%.

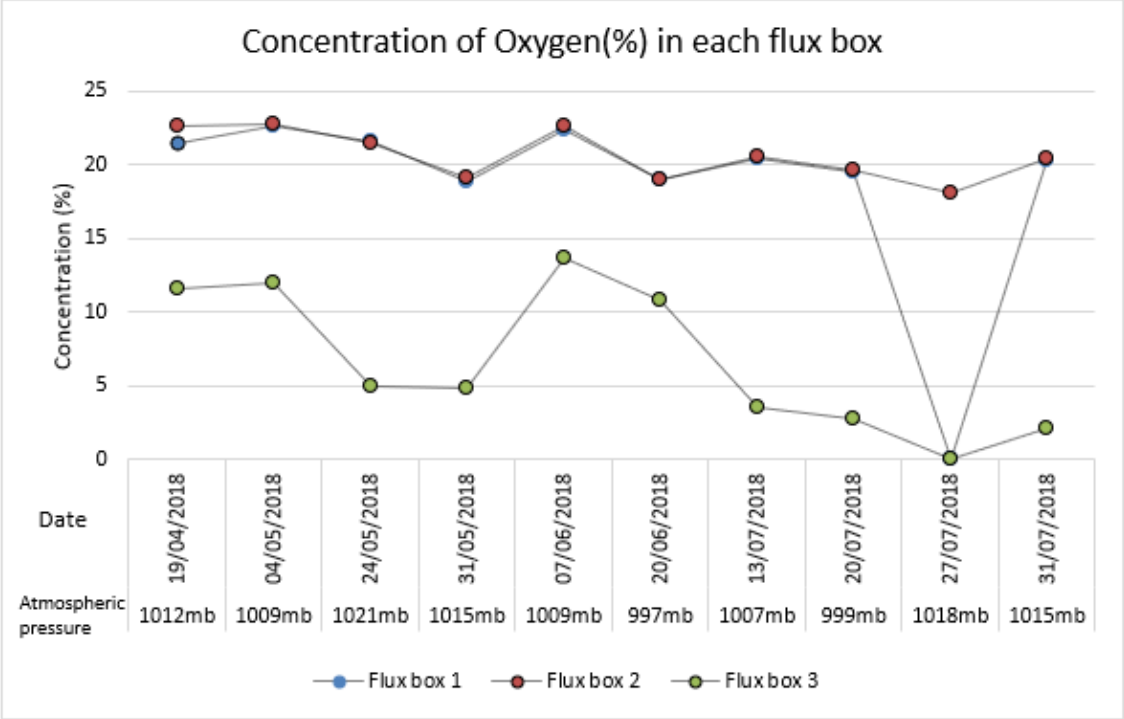


Figure 6.4 Concentration of oxygen (%) in each flux box during gas measurement

Figure 6.4 shows the measurement details of oxygen. As described in the Figure 6.4, concentration of oxygen above the waste layer (flux box3) was lower than the value above impermeable layer (flux box2) and LLDPE membrane (flux box1). Concentration of oxygen above the waste layer and above the impermeable layer was between 0 – 13.7% and 18.1% - 22.8% respectively. Concentration of oxygen above the LLDPE membrane varied between 18.9% - 22.6%, except once. Since gas analyser was unable to measure the oxygen concentration on 6.8.2018, concentration of oxygen could not be measured during the last measurement.

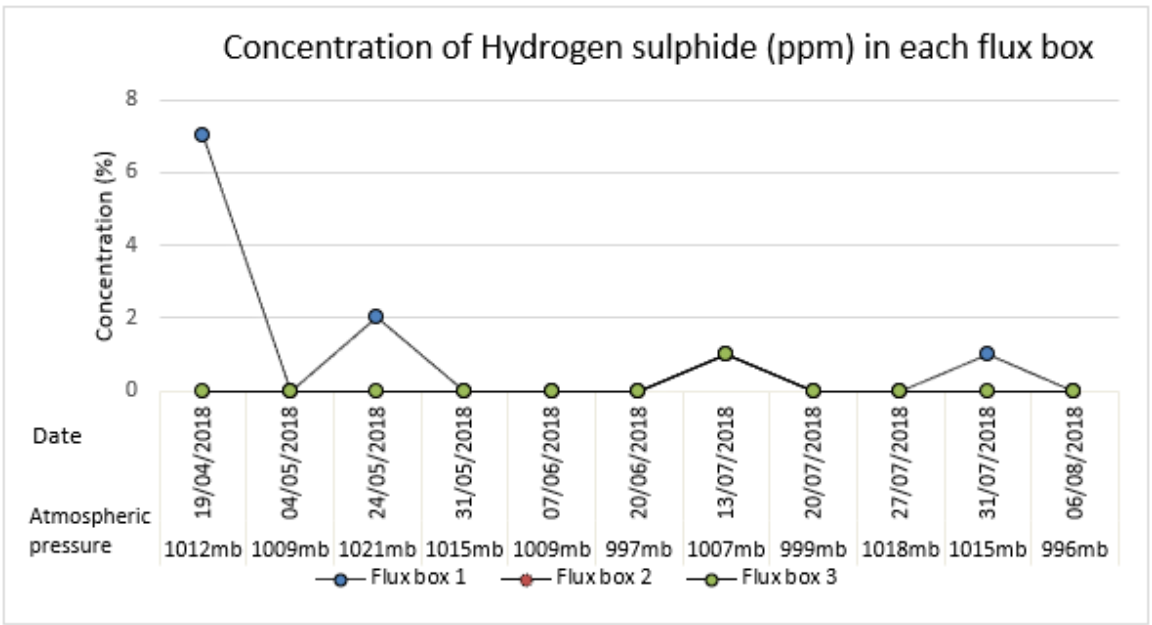


Figure 6.5 Concentration of hydrogen sulphide (ppm) in each flux box

Figure 6.5 shows the measurement details of hydrogen sulphide. As described in the figure 6.5, in most of the measurement, concentration of hydrogen sulphide was zero ppm in all flux boxes. Maximum value of 7ppm was measured during the first measurement. The concentration of hydrogen sulphide was 0-2ppm in the all other gas measurements.

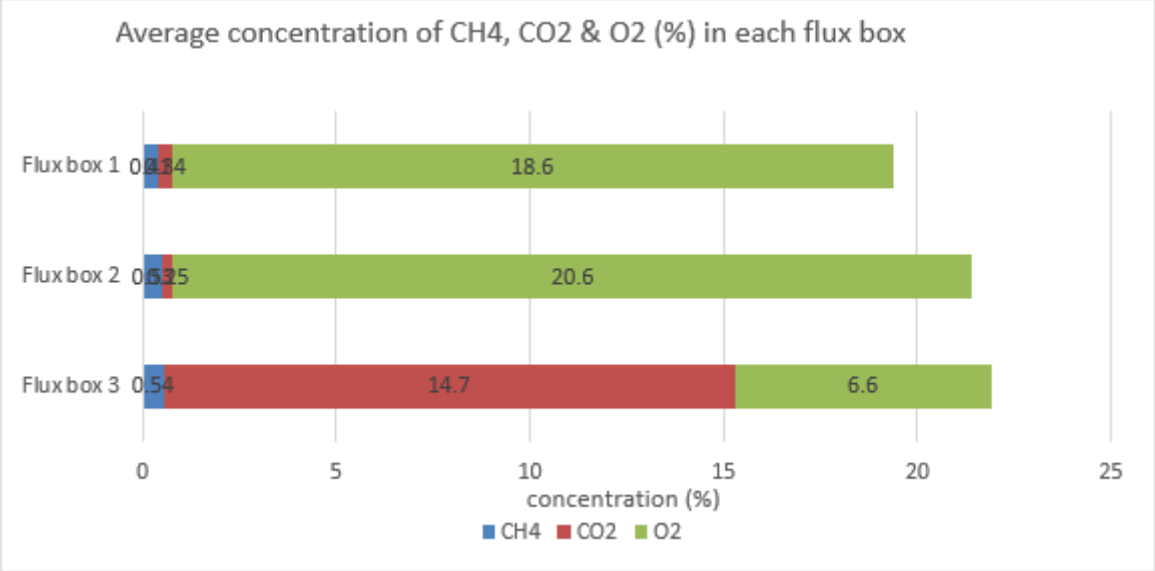


Figure 6.6 Average concentration of methane (CH_4), carbon dioxide (CO_2) and oxygen(O_2) (%) in each flux box during gas measurement period

Figure 6.6 shows the average concentration of methane, carbon dioxide and oxygen in each flux boxes. According to the Figure 6.6, average concentration of methane and carbon dioxide above the waste layer (flux box3) was lower than that of a typical landfill gas. Average concentration of methane did not have a considerable variation between the measurements in each flux boxes. Average concentration of carbon dioxide in flux box2 (above the impermeable layer) and flux box1 (above the LLDPE membrane) were 0.2% and 0.3% respectively. This is very low compared to flux box3 (above the waste layer). Average concentration of carbon dioxide reported in flux box3 was 14.7%. Average concentration of oxygen was 6.6 % above the waste layer (flux box3) and it was lower than oxygen concentration above the impermeable layer (flux box2) and LLDPE membrane (flux box1). High oxygen concentration above the impermeable layer and the LLDPE membrane shows the presence of atmospheric air in the flux boxes 1 and 2.

Figure 6.7 shows the average concentration of hydrogen sulphide during the gas measurement period. Concentration of hydrogen sulphide was very low in every measurement and the average concentration above the waste layer (flux box3) was only 1ppm.

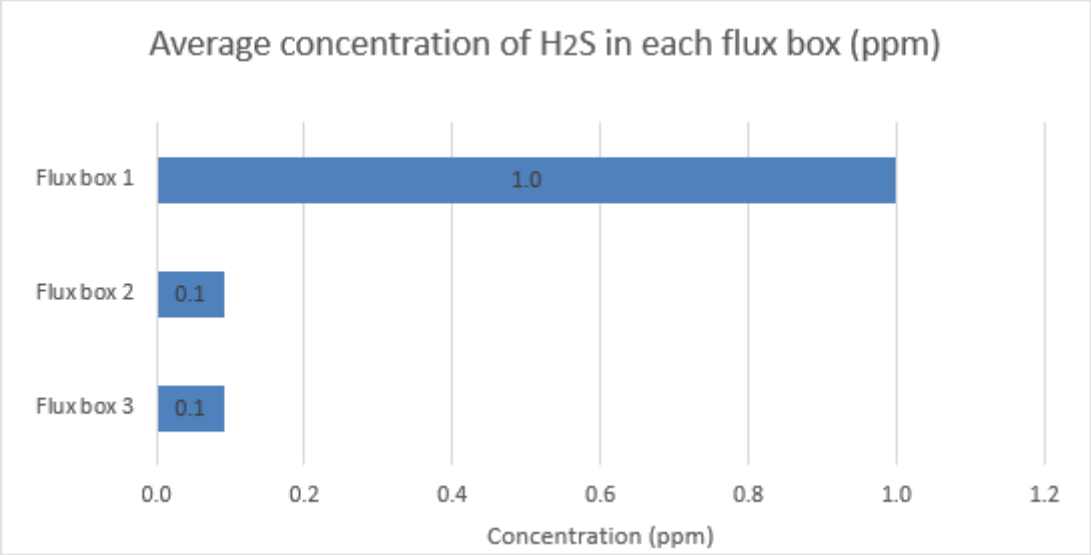


Figure 6.7 Average concentration of hydrogen sulphide (H_2S) (ppm) in each flux box during gas measurement

6.3 Gas measurement result from the 2017 test structure

Gas measurements from 2017 structure were taken during 12.04.2018 – 6.8.2018. During the gas measurement period, the gas collection system from the D8 well was either ON (valve open) or OFF (valve closed). Controlling gas collection valve as opened or closed, was done for studying the concentration variation of gas components in the structural layers with the gas collection. The gas collection well D8 was situated in the middle of the structure. The gas collection well was connected to the gas collection centre by using a gas collection pipe. The gas collection was controlled by a gas collection valve in the gas collection centre. For collecting the gas, suction was applied in the gas collection pipe. When the gas collection was ON, gas was collected from the waste layer through gas collection pipe. When the gas collection was OFF, or when there was no gas flow from the gas collection pipe, higher gas pressure can be in the waste layer under the cover structure than when the gas collection was ON. In the beginning and in the end of gas measurement period, measurements were taken when the gas collection was OFF. In the middle period, measurements were taken during the gas collection was ON. Rate of gas flow through the gas collection pipe varied during the gas collection period. All gas measurement data of 2017 test structure is included in Appendix 6.

In 2017 test structure, gas measurements were started on 12.4.2018. First measurements were done in the existing conditions. Accordingly, during the first measurement, flow rate from the D8 gas collection well was 0.1m^3/h. Gas flow rate and the gas concentration in the gas collection pipe was measured in SA13 gas collection centre. The gas valve of D8 collection well was completely closed after the first measurement. Next two measurements on 16.04.2018 and 19.04.2018 were taken with completely closed valve condition. The gas collection valve from D8 well was opened by 21% few days before 4.05.2018. Exact date of opening was not available. The next gas measurements were taken when the gas collection was ON. Again, gas collection was OFF on 27.07.2018 just before the measurements taken on that day. Thus, the last three measurements were taken when the gas collection was OFF.

Gas measurements were taken from the Gas Collection layer (GCL), Lower Check Layer (LCL) and Upper Check Layer (UCL). Average concentration of each landfill gas component in each layer is the average of each gas component concentration measured from the four observation pipes in each layer. Gas concentration of D8 is also illustrated in the graph for comparison. Concentration of methane, carbon dioxide and oxygen are given in percentage (%) by volume and concentration of hydrogen sulphide is given in parts per million(ppm).

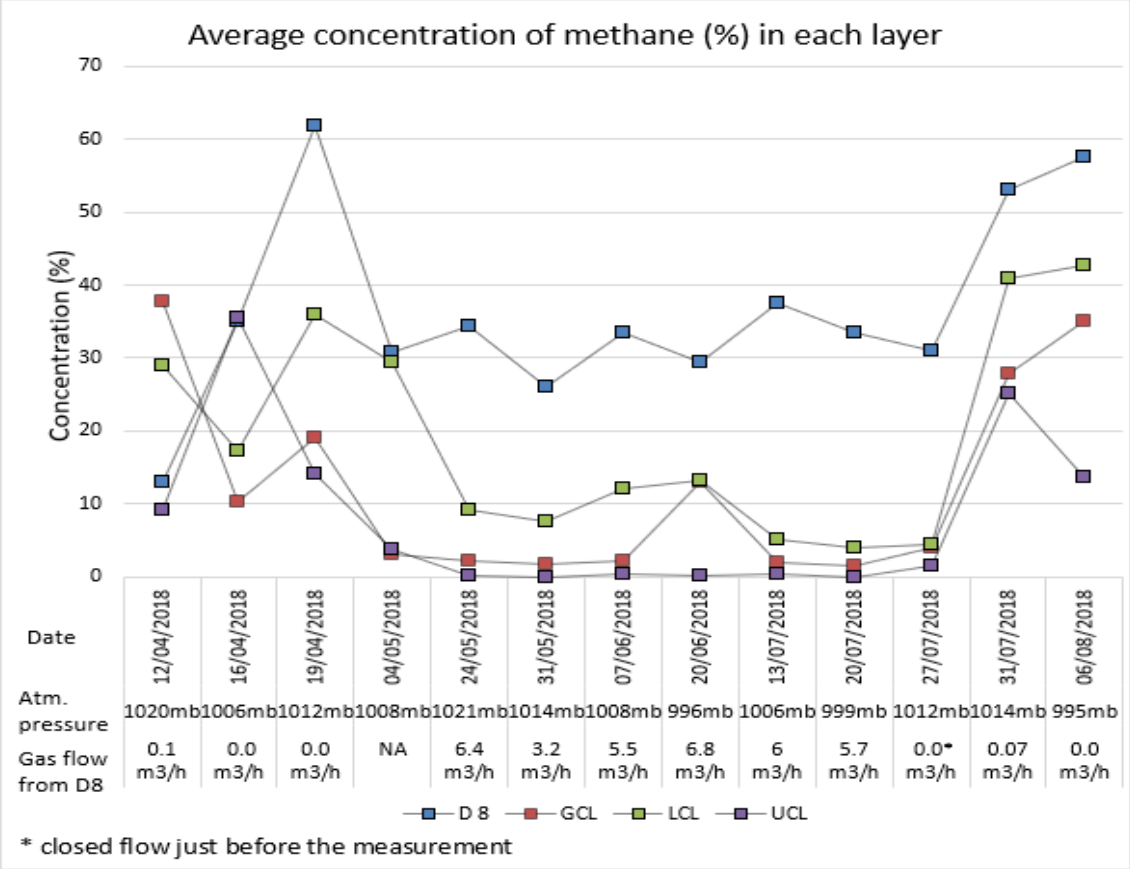


Figure 6.8 Average concentration of methane (%) in each layer during the gas measurement period

Figure 6.8 shows the average concentration of methane during the gas measurement period. As illustrated in the Figure 6.8, the measured concentration of methane was higher in GCL, LCL and UCL during the period when the gas collection from D8 was OFF, compared to the gas collection was ON. When the gas collection was ON, measured concentration of methane was very similar in all layers. When the gas collection from D8 was OFF, maximum value of average concentration of methane in structural layers was 42.6% (measured in the LCL which is situated above the reaction layer). During the same measurement period, concentration of methane in the gas collection pipe (D8) was 57.6% only. Throughout the gas measurement period, average concentration of methane was higher in lower check layer (LCL) than in the gas collection layer (GCL). The value was around zero in upper check layer (UCL) when the gas collection was ON. When the gas collection was OFF, methane concentration was also considerably increased in the upper check layer (UCL). When the gas collection was ON, methane concentration in gas collection layer (GCL) was low and was around 2% except once.

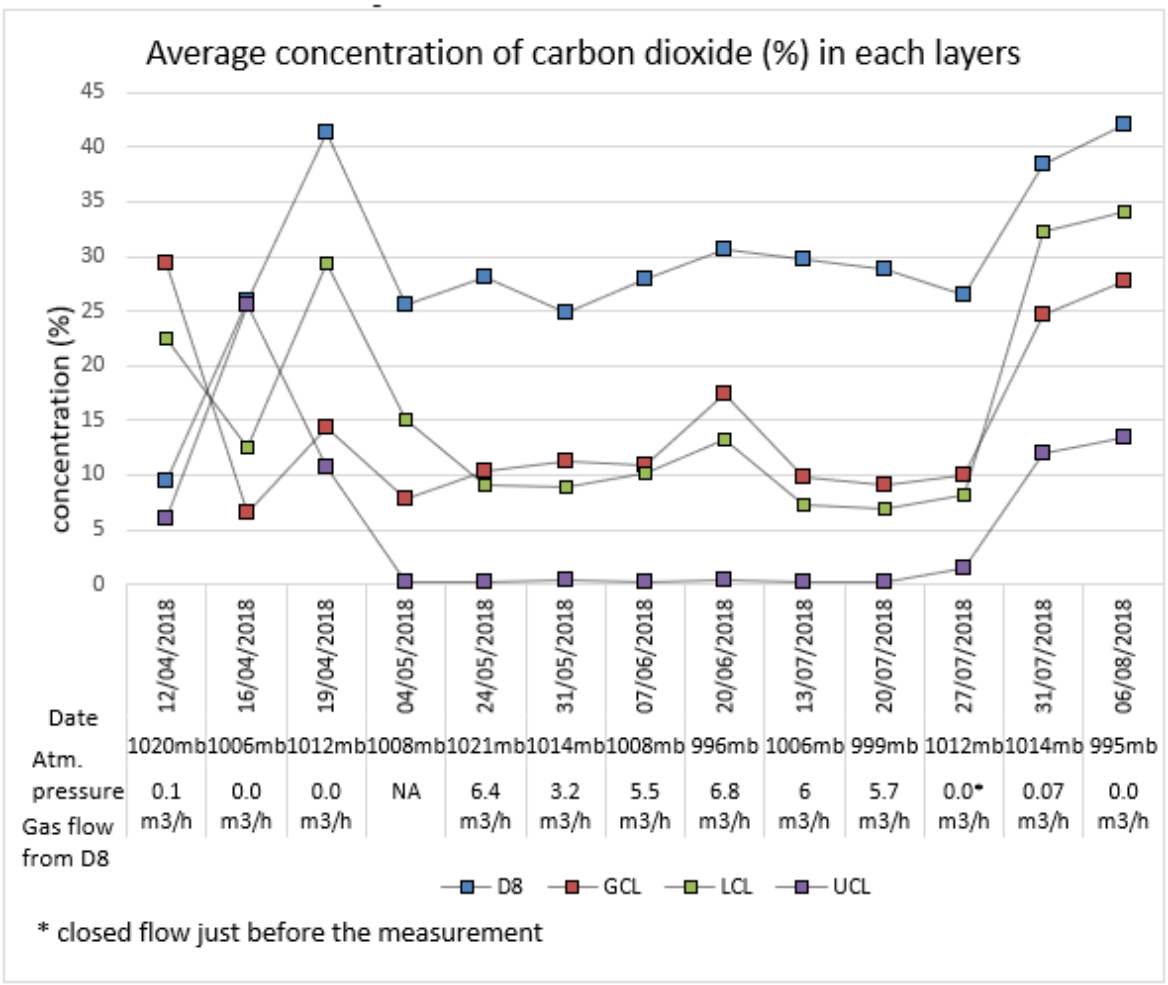


Figure 6.9 Average concentration of carbon dioxide (%) in each layer during the gas measurement period

Figure 6.9 shows the average concentration of carbon dioxide during the gas measurement period. As illustrated in the Figure 6.9, the average concentration of carbon dioxide was also higher during the period when gas collection was OFF than when the gas collection was ON. When the gas collection was ON, average carbon dioxide concentration was near to zero in the upper check layer (UCL). Carbon dioxide concentration was very similar to methane concentration. However, in gas collection layer (GCL), average carbon dioxide concentration was higher than the methane concentration.

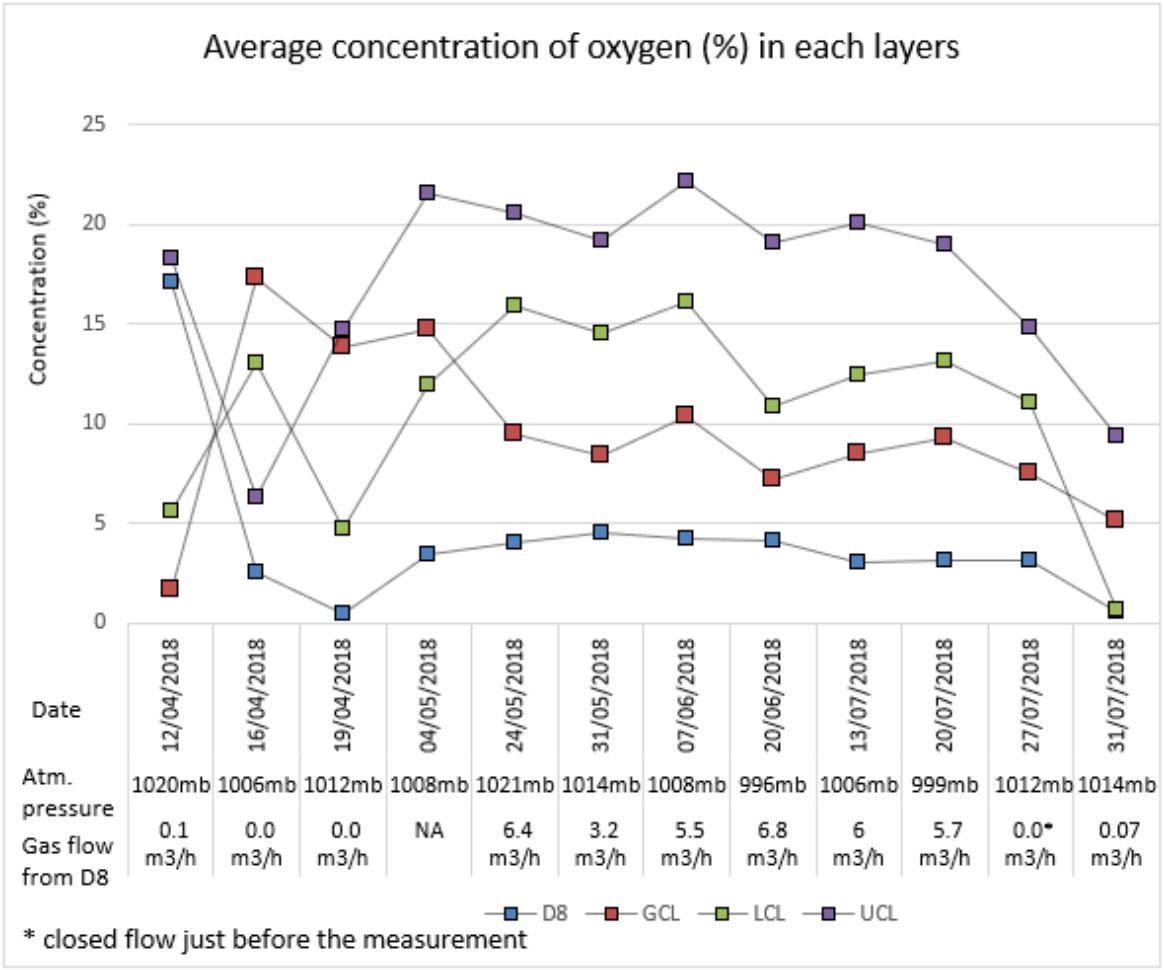


Figure 6.10 Average concentration of oxygen (%) in each layer during the gas measurement period

Figure 6.10 shows the average concentration of oxygen during the gas measurement period. As illustrated in the Figure 6.10, average oxygen concentration in structural layers was decreasing from top to bottom when the gas collection was ON. Maximum oxygen concentration was in upper check layer (UCL) and minimum was in gas collection layer (GCL). However, most of the time, oxygen concentration in the structural layers were measured to be higher than in a typical landfill gas.

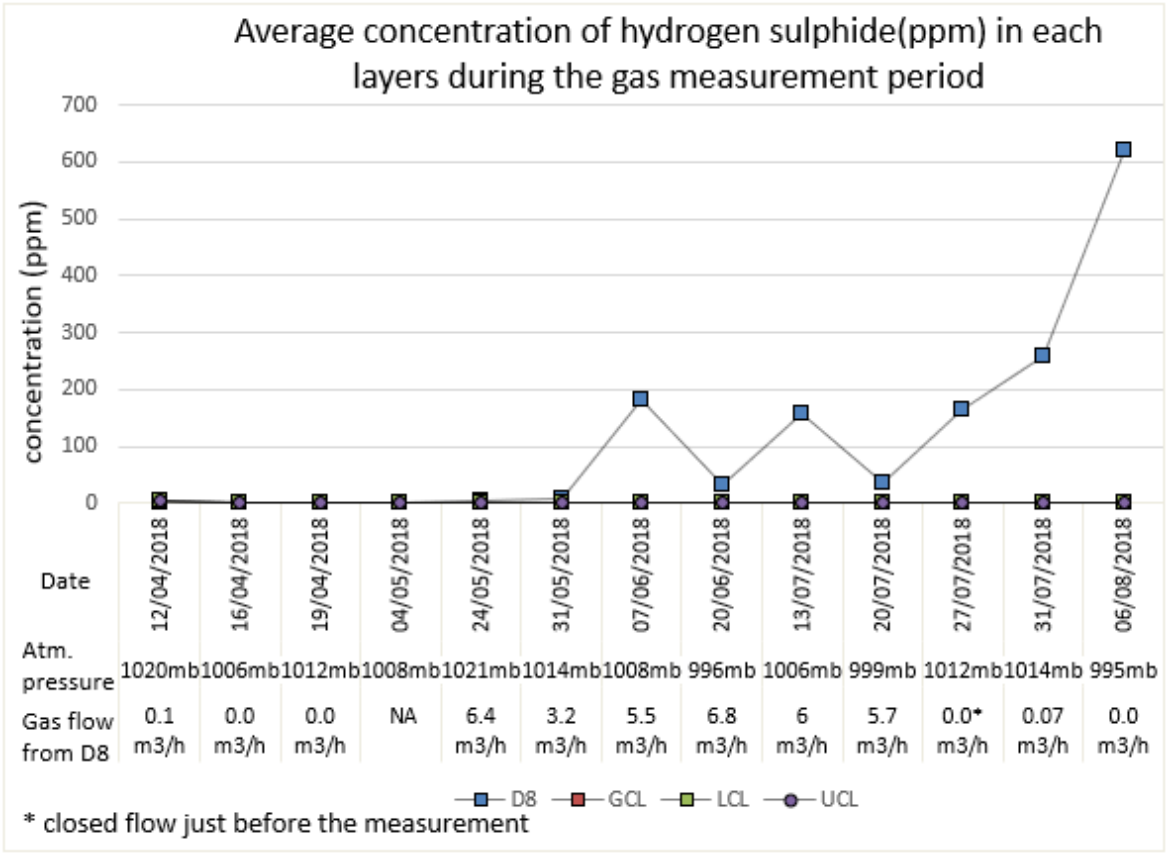


Figure 6.11 Average concentration of hydrogen sulphide (ppm) in each layer during the gas measurement period

Figure 6.11 shows the average concentration of hydrogen sulphide during the gas measurement period. As described in the Figure 6.11, average concentration of hydrogen sulphide was considerably low in all structural layers compared to D8 gas collection well. Measured values of hydrogen sulphide concentration were in between 0–2ppm, except for the first measurement. In the first measurement, concentration of hydrogen sulphide was in between 0-16ppm. The measured concentration of hydrogen sulphide in the D8 gas collection well was in between 0-619ppm.

Figure 6.12 shows the average gas concentration of methane, carbon dioxide and oxygen in the structural layers when the gas collection was ON and OFF. Since gas collection condition was uncertain, gas measurements on 12.04.2018 and 4.5.2018 were not considered here. As illustrated in the Figure 6.12, when the gas collection was ON, in all layers, methane and carbon dioxide concentration was low when compared to the gas collection OFF case. When the gas collection was OFF, considerable amount of methane and carbon dioxide reached up to upper check layer (UCL). However, when the gas collection was ON, concentration of these gases was almost zero in the upper check layer. When the gas collection was OFF, lower check layer (LCL) had higher concentration of methane and carbon dioxide than gas collection layer (GCL). Even when the gas collection was ON, concentration of methane in lower check layer (LCL) was higher than in the gas collection layer (GCL). However, concentration of carbon dioxide was lower in lower check layer (LCL) than gas collection layer (GCL).

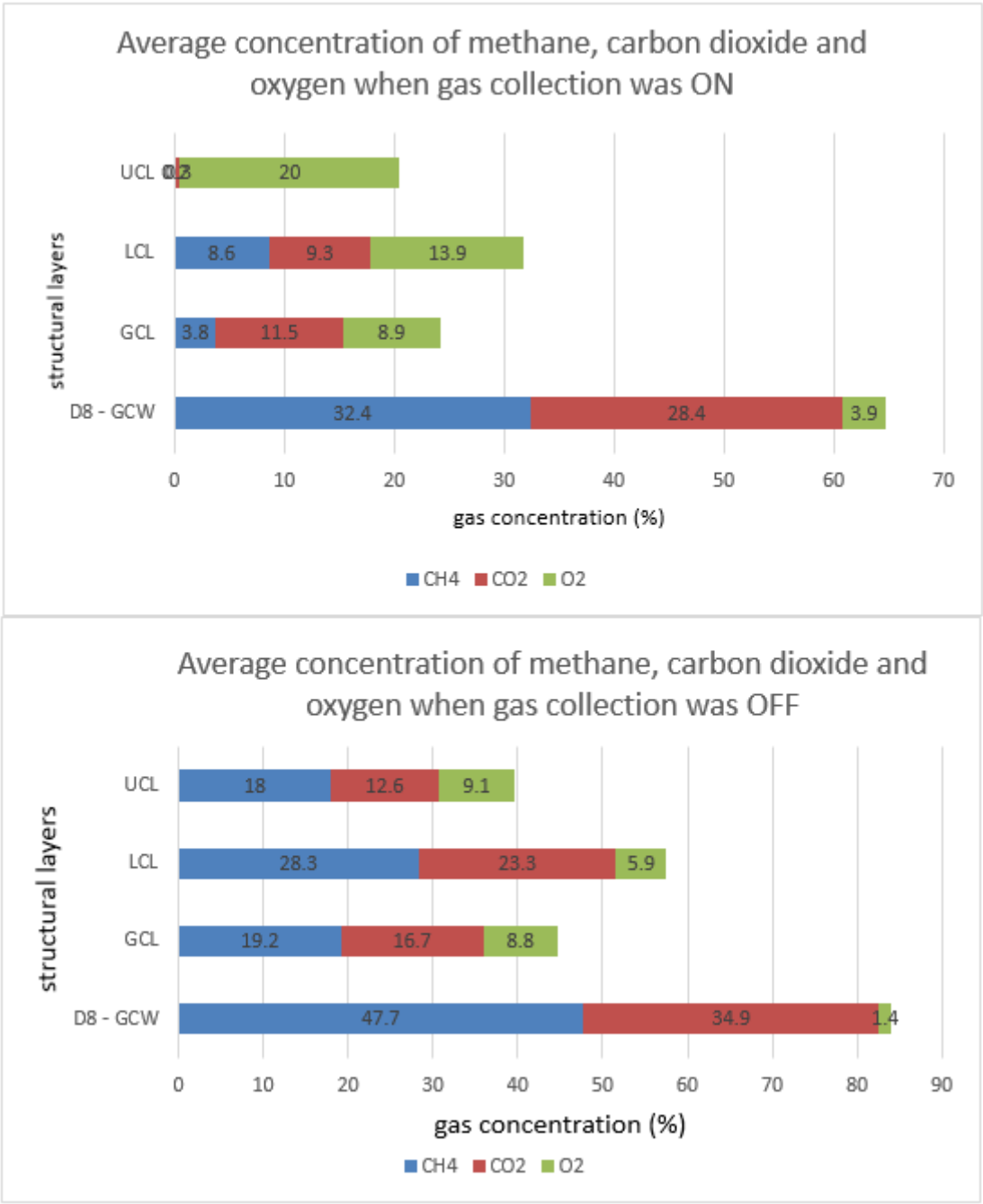


Figure 6.12 average concentration of methane, carbon dioxide and oxygen when the gas collection was ON and OFF

Figure 6.13 shows the average concentration of hydrogen sulphide when gas collection was ON and OFF. Even though, concentration of hydrogen sulphide was high in gas collection pipe (D8), it was between 0-0.4ppm in structural layers when the gas collection was ON and OFF.

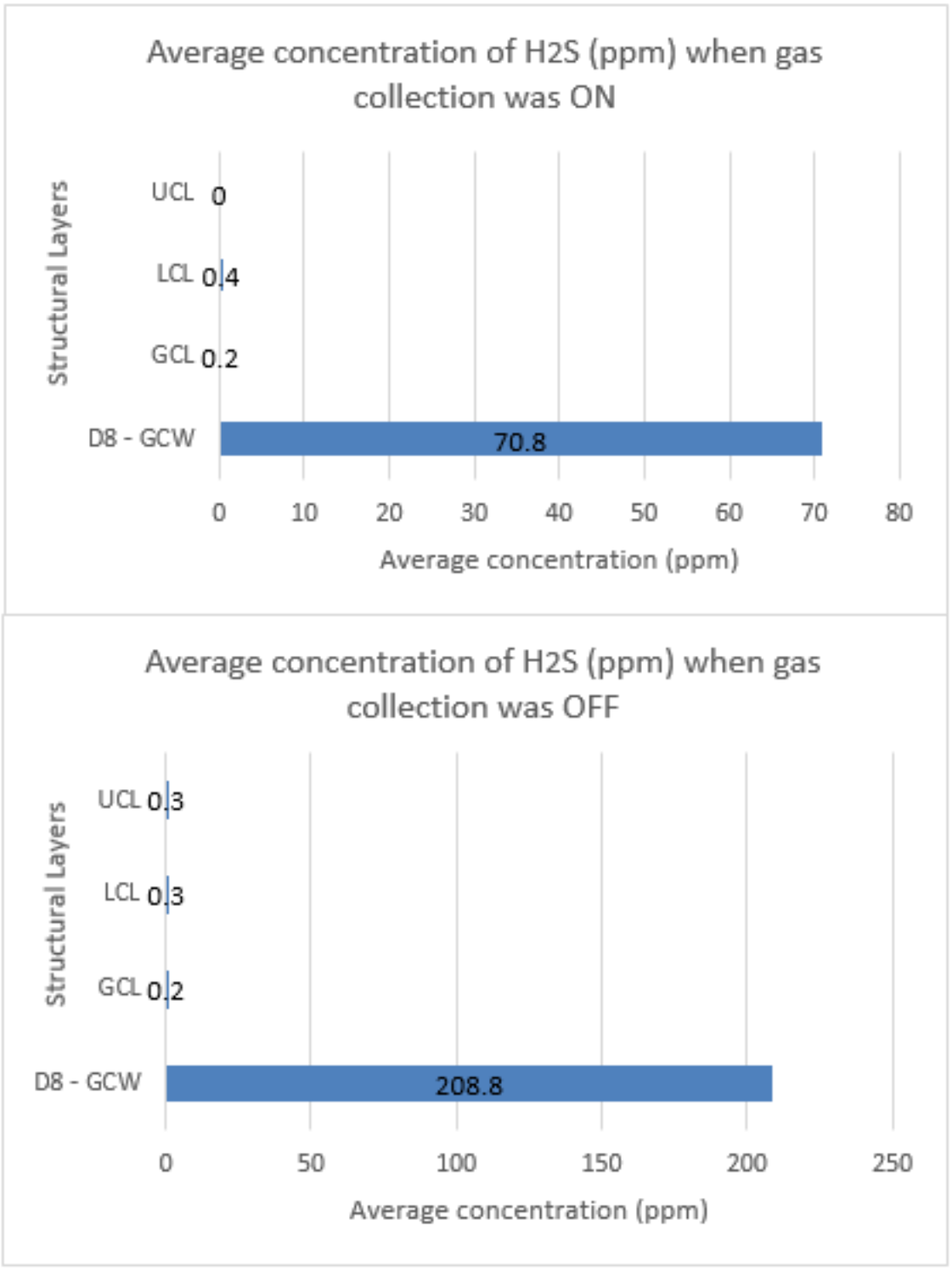


Figure 6.13 average concentration of hydrogen sulphide when the gas collection was ON and OFF.

Figure 6.14 shows the average concentration of methane, carbon dioxide and oxygen in structural layers and gas collection pipe during the gas measurement period 12.04.2018 – 06.08.2018.

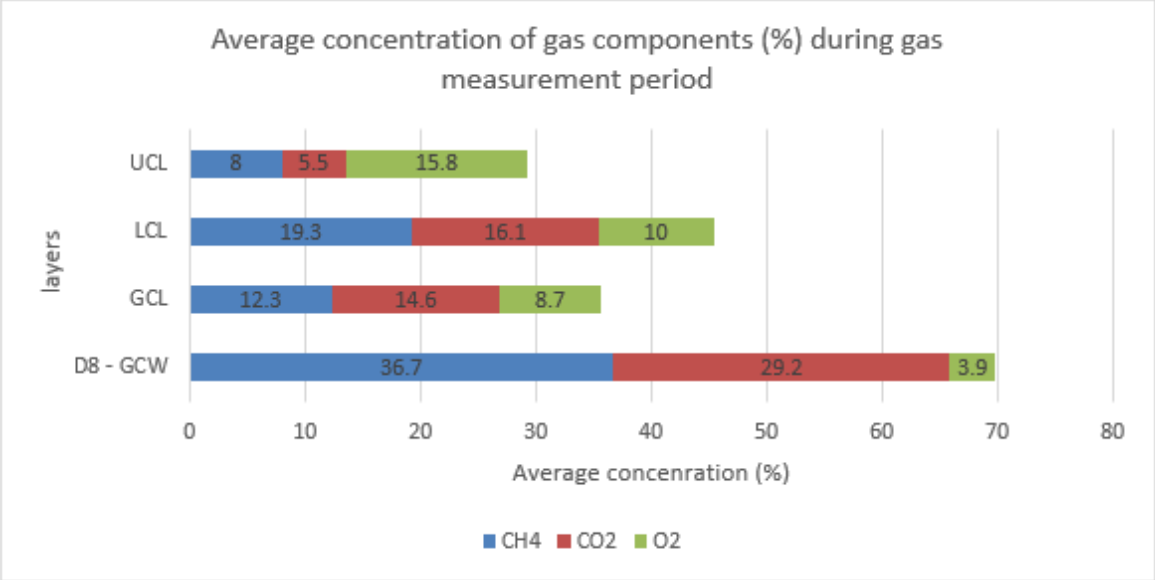


Figure 6.14 average concentration of methane, carbon dioxide and oxygen during gas measurement period 12.04.2018 – 06.08.2018

Figure 6.15 shows the average concentration of hydrogen sulphide during gas measurement period 12.04.2018 – 06.08.2018. Average concentration of hydrogen sulphide was between 0.4-0.7ppm in every structural layer during gas measuring period.

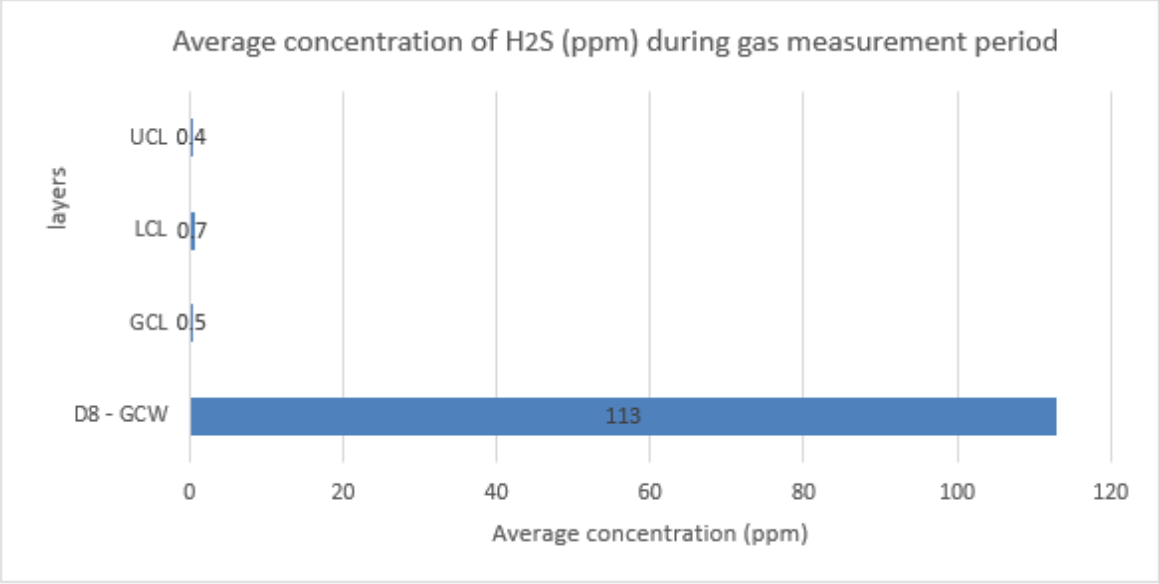


Figure 6.15 average concentration of hydrogen sulphide during gas measurement period 12.04.2018 – 06.08.2018

Figure 6.16 shows the average concentration of methane, carbon dioxide and oxygen in each observation pipe (1-4) of gas collection layer (GCL), lower check level (LCL) and upper check level (UCL) during the gas measurement period.

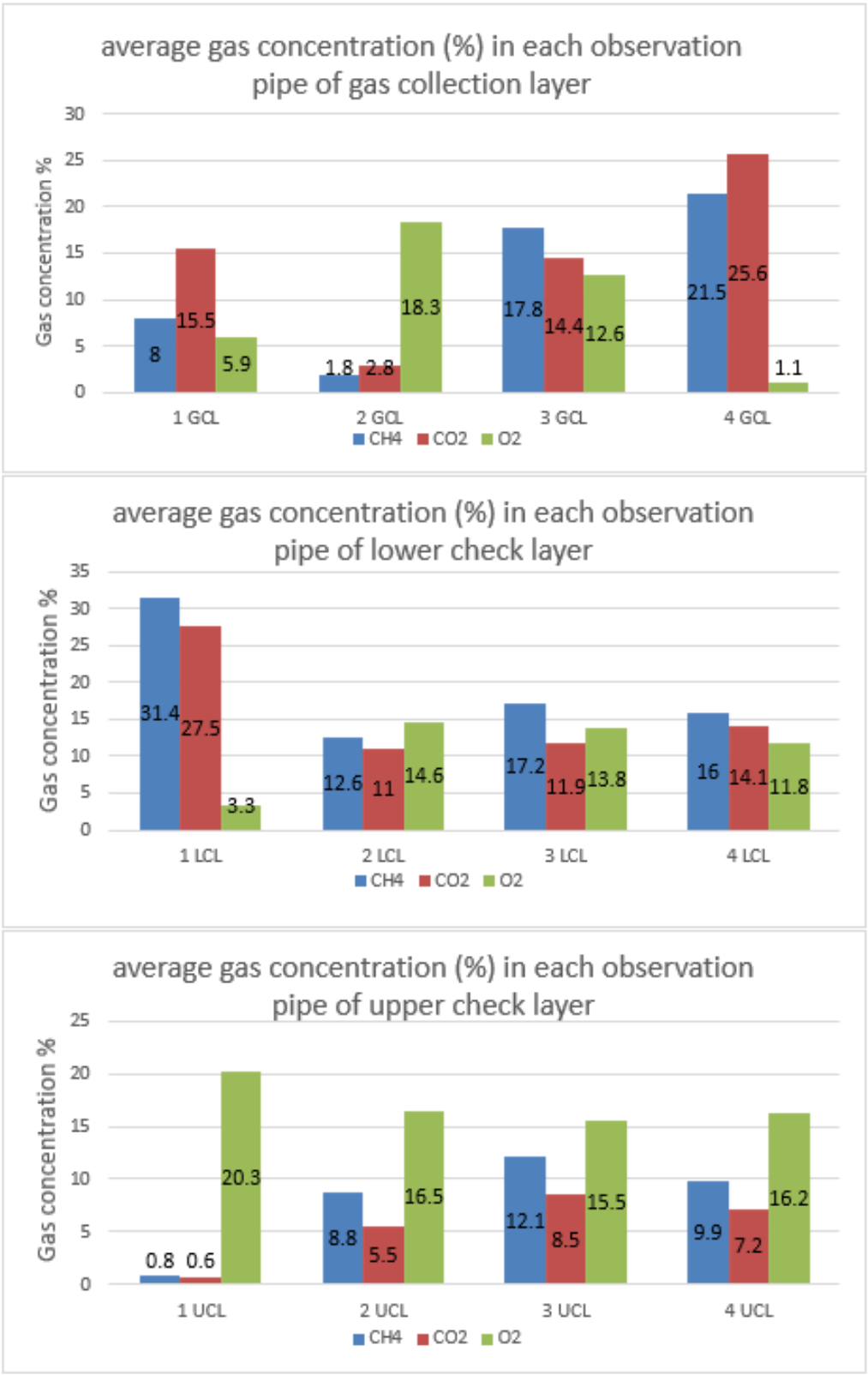
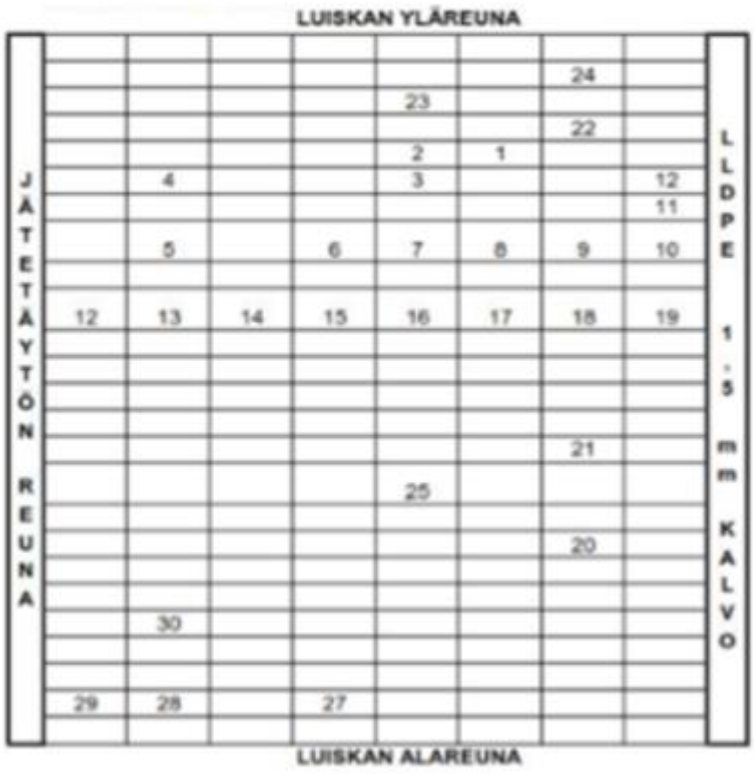


Figure 6.16 average concentration of methane, carbon dioxide and oxygen in each observation pipe of GCL, LCL and UCL during the gas measurement period

As described in the Figure 6.16, concentration of gases measured from each observation pipe in the same layer varies significantly. For instance, measured concentration of carbon dioxide from the fourth observation pipe of gas collection layer (4GCL) was about nine times higher than in the second observation pipe (2GCL). Similar kind of variations in methane concentration were also observed in other layers. Considerable difference in 1LCL & 2LCL as well as 1UCL & 3UCL. Therefore, concentration of gas component from only one observation pipe cannot be considered as a representative value of a structural layer.

6.4 Surface methane emission measurement result from the 2015 test structure

Surface methane emission measurement from 2015 test structure was done during 2017 before this research study was started. Measurement was conducted above the impermeable layer when the structure was opened. Figure 6.17 shows the surface methane emission measurement (methane emission measurement) result of the structure. Left part of the figure represents the site and the numbers from 1 to 30 represents number of each measurement points. Right part of the figure represents the measurement results corresponding to the points 1 – 30.



Nro.	Huom.	Mittaus-tulos (ppm)
1	Troxler-reikä	20
2	10 cm reijästä	25
3	vsiym. Kuoppa	20
4	vsiym. Kuoppa	20
5		1
6		4
7		5
8		30
9		43
10		50
11	Huom. Reuna, kalvon alta	100
12		1
12.1	Huom. Reuna, kalvon alta	2000
13		1
14		0
15		25
16		37
17		35
18	Huom. Reuna, maltti kalvon alta	650
19		55
20		39
21		70
22		50
23		13
24		27
25		33
26		16
27		5
28		29
29		50
30		15

Figure 6.17 methane emission measurement result from 2015 structure done with DP-IR methane detector (HSY, 2018b)

Measured methane concentration was in between 0-70ppm except at the edges of the opened area under the LLDPE membrane. At the edges measured methane concentration was in between 100-2000ppm.

6.5 Surface methane emission measurement result from the 2017 test structure

In the 2017 test structure, surface methane emission measurement was done using DP-IR methane detector on 27.8.2018. Measurements were taken from the surface and slope of the 2017 test structure. Additional measurements were also taken from the area around the observation pipes. Table 6.1 shows the methane emission measurements around the observation pipe and figure 6.18 shows the methane emission measurements from surface of 2017 test structure. Concentration of methane measured from the surface and slope of the structure were mainly between 3-134ppm. High concentration of methane (2.73%) was measured at one point on the surface of structure. A crack was observed in that part. Measured concentration of methane from the area around the observation pipes show that there was considerable leakage of landfill gas around the observation pipe. The values were in between 25 ppm – 6.01%.

Table 6.1 Emission measurement around the observation pipe

Observation pipe	1 UCL	1 GCL	1 LCL	2 UCL	2 GCL	2 LCL	3 UCL	3 GCL	3 LCL	4 UCL	4 GCL	4 LCL
DP-IR reading around the observation	940 ppm	3.76%	370 ppm	23 ppm	35 ppm	1.25%	517 ppm	248 ppm	1016 ppm	6.01%	1.73%	116 ppm

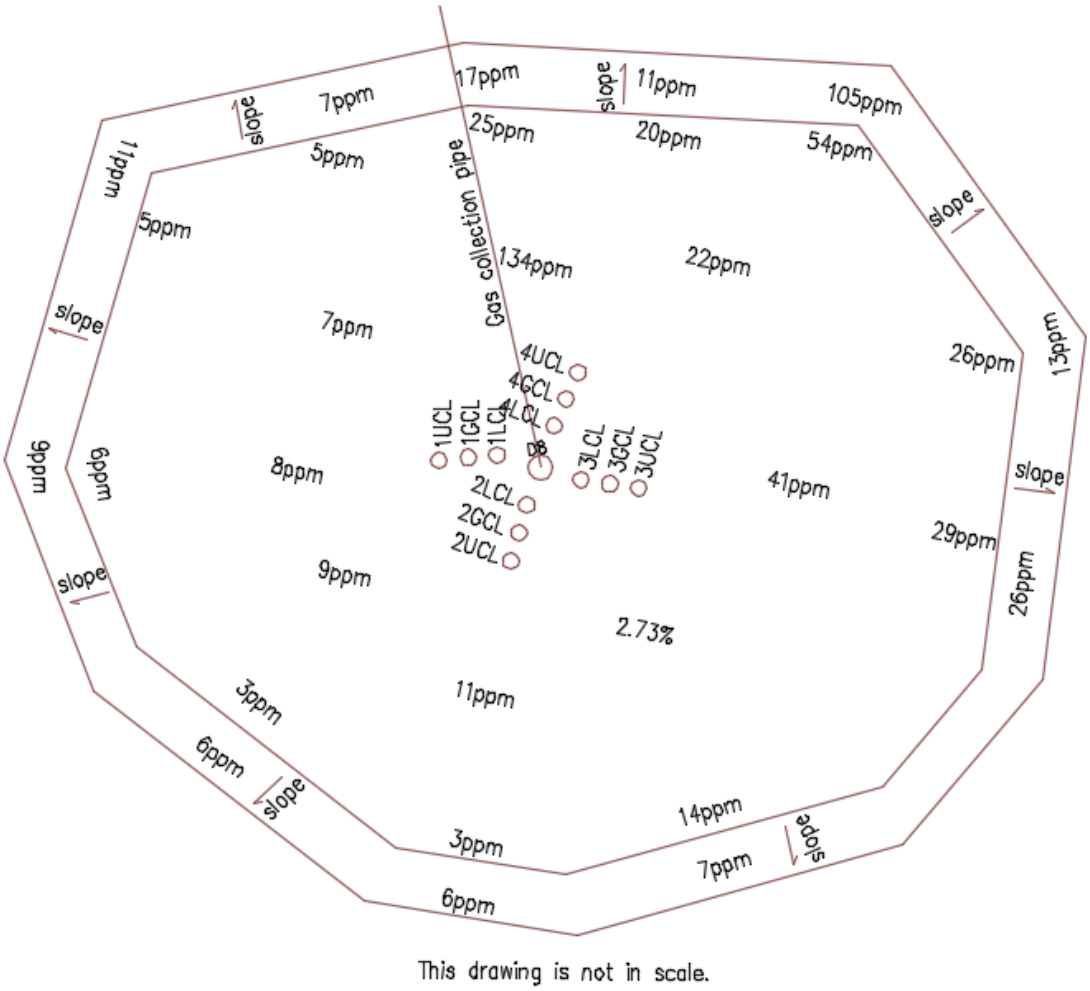


Figure 6.18 Surface methane emission measurement from the 2017 test structure

Presumably, the measured value of gas emission could have been lower than the normal level due to rain and clay cover over the structure. There was rain at the landfill area in the previous days before the measurement day and the land was wet. Since the increase in water content can decrease the gas emission, the measured value could have been lower than the normal level. Furthermore, since the landfill gas odour was detected at the structure during the first gas measurement time, it was assumed that the landfill gas odour was due to leakage from the structure. Thus, suspecting leakage from the structure, surface of the structure was covered with clay in the beginning of this research study. This was done for getting a reliable result from the structural layers. Pictures of the site when the half of the site was covered with clay and after fully covered with clay included in the Appendix 7.

6.6 Other observations during gas measurement

During the first measurement, trapped water was observed in the gas collection pipe. Water was removed from the gas collection pipe before taking next measurement. Gas collection pipe was also raised to a suitable level by heaping soil below the pipe to flow water smoothly inside the pipe.

7 Analysis on landfill test structures

This section first describes the gas measurement analysis of 2015 and 2017 test structures, Then, establishes the conclusion on gas permeability of the impermeable layers in the two test structures.

7.1 Gas measurement analysis of 2015- Test structure

Concentration of gas components above the impermeable layer and LLDPE membrane did not vary significantly during the gas measurement period. From the measured values, it seems that changes in atmospheric pressure did not significantly affect the gas emission from the 2015 Test structure.

Compared to typical landfill gas, in all measurements, concentration of methane was measured to be very low in all flux boxes. Typical landfill gas concentration of methane is 45% - 60%. Concentration of methane was considerably lower than the typical landfill gas even in flux box3 which was situated above the waste layer. However, the concentration of carbon dioxide was high compared to methane. Average concentration of carbon dioxide was 14%, whereas average methane concentration was 0.5%. The lower concentration of methane may be due to the less amount of available organic waste content in that area. However, collected gases from the nearest gas collection wells (A7 and B1) contained typical landfill methane concentration. These wells were situated very far from flux box 3 and the organic waste content around those wells could have been more than the waste around flux box 3. Average oxygen concentration in flux box 3 was 6.6%. This is higher than in a typical landfill gas. Typical landfill gas concentration of oxygen is 0.1-1%. In flux box 2 and 1, average oxygen concentration was near to atmospheric air and measured 20.6% and 20.7% respectively. Average oxygen concentration in atmospheric air is 21%. This shows that the atmospheric air could have been entered to the flux box 1 and 2.

The concentration of carbon dioxide above LLDPE membrane was same or higher than above the impermeable layer. However, average concentration of carbon dioxide above the impermeable layer was 98.3% lower than above the waste layer. This shows that cover structure is effective in reducing gas emission from the waste layer. This may be due to the low gas permeability of the impermeable layer. Another potential reason for the lower concentration of carbon dioxide in flux box 2 and 3 can be due to the reactivity of MSWI bottom ash with carbon dioxide. According to the studies (as described in Section 3.3), MSWI bottom ash can react with carbon dioxide and remove carbon dioxide from the landfill gas.

Hydrogen sulphide concentration was measured to be very low in all flux boxes during the gas measurement. It was in between 0 - 2 ppm in most of the measurements. During the first measurement in flux box 1, only once hydrogen sulphide concentration was measured 7ppm.

7.2 Gas measurement analysis of 2017-Test structure

During the gas measurement period, in every layer, there was a significant variation in the concentration of CH_4, CO_2 and O_2 observed in the individual observation pipes. This may

be due to the differences in gas permeability of the area around the bottom of individual observation pipe.

There were differences in the measured gas concentration in different layers when the gas collection system was ON and OFF. The measurement results also show that there was a considerable difference in the concentration of gas components in the two stages. When the gas collection was ON, the average concentration of landfill gas components in each layer was considerably low compared to the case, when gas collection was OFF. For instance, when the gas collection was OFF, average concentration of methane in the lower check layer was 19.7% more and the concentration of carbon dioxide was 14% more, against when the gas collection was ON. There was a similar increase in the concentration of methane and carbon dioxide in the upper check layers, with the gas collection OFF. This shows the significance of gas collection in reducing the gas emission through the cover structure. In other words, when gas collection was OFF, and when more gas pressure develops under the reactive layer, the gas emission increased through the reactive layer significantly. However, the concentration of methane and carbon dioxide in the lower check layer when the gas collection was ON also not at the negligible amount. This shows the gas permeability of the structure is high or there can be some potential cracks in the structural layers.

Concentration of hydrogen sulphide was very low in the structural layers during gas measurement period. However, during this period, there was a considerable amount of hydrogen sulphide in the collected gas from D8 gas collection well. In the first measurement, there was presence of H_2S in most of layers. This may be due to the gathered hydrogen sulphide during a long period of time before the measurements. From the second measurements onwards, measured concentration of hydrogen sulphide was very negligible and was in between 0 – 2ppm. Low concentration of hydrogen sulphide in the structural layers can be due to the reaction of hydrogen sulphide with MSWI BA.

However, since the concentration of carbon dioxide was high in the layers above the reactive layer of this test structure, reactivity of bottom ash with carbon dioxide did not have significant effect in removing carbon dioxide from the landfill gas. This can be due to the lack of favouring factors for reaction of bottom ash with carbon dioxide. Reactivity of carbon dioxide depends upon several factors such as available calcium content for reaction, pressure of CO_2, moisture content, reaction time, etc.

According to some earlier studies (Hakkarainen, 2013), reduction in the concentration of carbon dioxide in the upper layers can be due to the reactivity effect of MSWI BA with carbon dioxide. However, in the 2017 structure, it was not observed any significant decrease in concentration of carbon dioxide above the reactive layer. Measured concentration of carbon dioxide was lower than the D8 collection well only when the gas collection was active. From the gas measurements, assumption can be made that the gas permeability of the 2017 test structure was high. Thus, the high gas permeability could have decreased the pressure and contact time between carbon dioxide with bottom ash and thereby decreased the reactions. In the Hakkarainen's study, there was an impermeable layer with low permeability above the reactive layer was used. Water permeability of the impermeable layer used in the Hakkarainen's study was in between $9{,}6x10^{-11}$ - $6x10^{-10}$ m/s. So, the impermeable layer might have restricted the gas flow and gas could have been kept in contact with the reactive layer for a longer time. This should have given more reaction time and gas pressure for carbon dioxide and bottom ash, resulted in the reduction of carbon dioxide. Furthermore,

coefficient of water permeability of the construction material used in the impermeable layer of this structure (bottom ash 0-5mm) with 92% compaction was higher ($5.7x10^{-8}$ m/s) than in the Hakkarainen's study.

Surface methane emission measurements from 2017 test structure with DP-IR instrument shows that the methane is emitted from the structure. Emission was more around the observation pipes than from the surface. According to the Australian guidelines, corrective actions should be taken when the methane concentration is greater than 500ppm at the leaking points. It was measured more than 500ppm of methane in some points of the 2017 test structure.

7.3 Conclusions of the test structures

In the 2015 test structure, average concentration of carbon dioxide above the impermeable layer was 98% less than above the waste layer. Methane and hydrogen sulphide concentration were also measured to be very low in the 2015 test cover structure. Coefficient of water permeability (k) for the mixture (MSWI BA and 3% polymer modified sodium bentonite) used for constructing the 2015 test structure was $1.1x10^{-10}$m/s, which is lower than the required value of $1x10^{-9}$m/s. This explains, why the gas permeability of the 2015 test structure is low and the structure is effective in controlling the landfill gas emission. Lower concentration of carbon dioxide above the impermeable layer can be also due to the higher reactivity of BA, which could have been influenced by the lower permeability of the layer. The bottom ash 0-2mm used in the 2015- structure was finer bottom ash than in 2017 structure and may be contained more Calcium. Since the hydrogen sulphide concentration in all layers was at the lowest level, reactivity of MSWI BA on the hydrogen sulphide removal cannot be clearly established from this analysis.

In the 2017 test structure, there was no significant reduction in the concentration of carbon dioxide and methane above the reactive (impermeable) layer. Average concentration of carbon dioxide above the reactive layer was 1.5% higher than in the gas collection layer. Average methane concentration above the reactive layer was also high (7% higher than in the gas collection layer). Higher concentration of gas components in the upper layers can be due to high permeability of the impermeable layer or due to cracks in the layers. During the laboratory tests, MSWI BA could able to achieve the water permeability coefficient (near to the recommended value) only at the high degree of compaction. However, it is not sure whether the similar compaction was achieved at the site. Even though hydrogen sulphide concentration in the gas collection well was 113ppm, concentration of hydrogen sulphide was only 0.5ppm in the gas collection layer. This can be due to the reactivity of MSWI BA with hydrogen sulphide.

From the analysis, it can be stated that 2017 test structure is less effective in controlling the landfill gas emission compared to 2015 test structure.

8 Experimental study of MSWI BA-Clay mixture

From the gas measurements study of 2015 and 2017 test structures, it is observed that the reactive layer (impermeable layer) of 2017 test structure was not effective for reducing the gas emission. The potential reason found for cause was the coefficient of water permeability of the reactive layer in 2017 test structure was higher than the impermeable layer of 2015 test structure. Therefore, the water permeability of the bottom ash used in the reactive layer of the cover structure had to be reduced to the required value.

According to the laboratory test done by Ramboll, the lowest water permeability $5.7x10^{-8}$ m/s was reported for 92% compacted 0-4mm MSWI bottom ash. However, when the degree of compaction decreased by 5%, the water permeability of the material was increased by 100 times. In construction sites, it may be difficult to achieve more than 92% of compaction with the bottom ash. Therefore, to ensure the low permeability $k<1x10^{-8}$m/s, extra materials which could reduce the water permeability had to be added with the bottom ash.

Bentonite and polymer modified bentonite were used for reducing the permeability in the previous studies. According to HSY, adding polymer modified bentonite with bottom ash was very expensive for the temporary cover construction and studies shows that, due to high pH of BA, ordinary bentonite does not swell effectively when it mixed with the bottom ash. Therefore, for reducing the permeability, these two bentonite types cannot be selected for this construction as an additive. Thus, as an economical solution, clay was selected for mixing with bottom ash. Clay has a very low water permeability $k\sim1x10^{-10}$ m/s and compacted clay was usually used for constructing impermeable layer of the landfill cover structure. Clay is usually considered as a waste soil in most of the construction sites in Finland and it is abundantly available too. This solution is very environmentally friendly and less expensive, since the two waste materials could be reused.

8.1 MSWI BA – clay mixing process

Mixing of MSWI BA-clay was done on 27.6.2018 in Ämmässuo soil mixing machine. Figure 8.1 shows the mixer system. It included two aggregate batchers, soil mixer, conveyer belt which can weigh soil and another conveying belt to shift the mixture from the mixer to the vehicle which carry the mixture and transport to the site. In addition to this, there was a control room to control the mixing process.

Figure 8.1 Mixer used in Ämmässuo

Clay for the MSWI BA-clay mixture was collected from a crop field. Collected clay was a mixture of wet clay (high water content) and dry crust (low water content). Before mixing with MSWI BA, two clays were separated with the loader bucket of the crawler loader. Then both the clays were smoothened separately with the loader bucket of the crawler loader to make it homogenous. These two clay types were used separately for making different mixtures with bottom ash. Two types bottom ash such as 0-5mm and 5-12.5mm particle size were used for making the mixtures. Figure 8.2 shows the figure of clay after separated as wet clay and dry crust.

Figure 8.2 separated wet clay (left) and dry crust (right)

Clay was shifted to an aggregate batcher and bottom ash was collected in another aggregate batcher. From there it was then moved to a conveyer belt and weight of the bottom ash and clay were measured on the conveyer belt. Five different proportions of MSWI BA-clay mixtures were made. The proportioning was done by weight. Table 8.1 shows the proportion of the mixtures.

Table 8.1 MSWI BA-clay mixtures

Mixture	Proportion of the mixture
1	60% clay (dry crust) + 40% BA(0-5mm)
2	40% clay (dry crust) + 60% BA(0-5mm)
3	60% clay(wet) + 40% BA(0-5mm)
4	40% clay(wet) + 60% BA(0-5mm)
5	40% clay(wet) + 60% BA(5-12.5mm)

Samples were compacted near the mixing plant using crawler loader and roller compactor. Vibrations were also applied during the compaction of the mixtures 1, 2 and 5. Constructability and homogeneity of the mixtures were checked during the compaction to study suitability of each mixture. Pictures taken during the compaction of the mixtures are included in the Appendix 8. Mixtures of MSWI BA 0-5mm with wet clay had a very poor constructability due to high water content in the mixture. During the compaction, MSWI BA -wet clay mixture stuck at the wheels of the crawler loader. In the mixtures with dry crust clay, 40% clay and 60% MSWI BA mixture had the highest homogeneity and constructability. Mixture of 40% wet clay with 5 – 12.5mm BA also had good homogeneity and constructability. Table 8.2 describes the homogeneity and constructability of the mixtures.

Table 8.2: Homogeneity and constructability of MSWI BA-clay mixtures prepared in Ämmässuo

Sample no.	sample	homogeneity	constructability	comments
1	60% clay(dry) + 40%BA(0-5mm)	Not good.	OK	Big clay clumps.
2	40% clay(dry) + 60% BA(0-5mm)	OK	OK	Good
3	60% clay(wet) + 40% BA(0-5mm)	Not good	Not OK	Big clay clumps and watery.
4	40% clay(wet) + 60% BA(0-5mm)	OK	Not OK	Watery
5	40% clay(wet) + 60% BA(5-12.5mm)	OK	OK	Good

Density and water content of the compacted mixtures were measured with Troxler moisture/density gauge at the site and by oven dry method in the laboratory by YIT company. Measurements are included in the Appendix 9. Samples from the mixtures (sample 1-5) were collected for further laboratory studies. In addition to those mixtures, samples of clay (sample 6), MSWI BA 0-5mm (sample 7), MSWI BA 5-12.5mm (sample 8) were also collected for laboratory tests. Figure 8.3 is the pictures of the samples 1-8 taken for the laboratory tests.

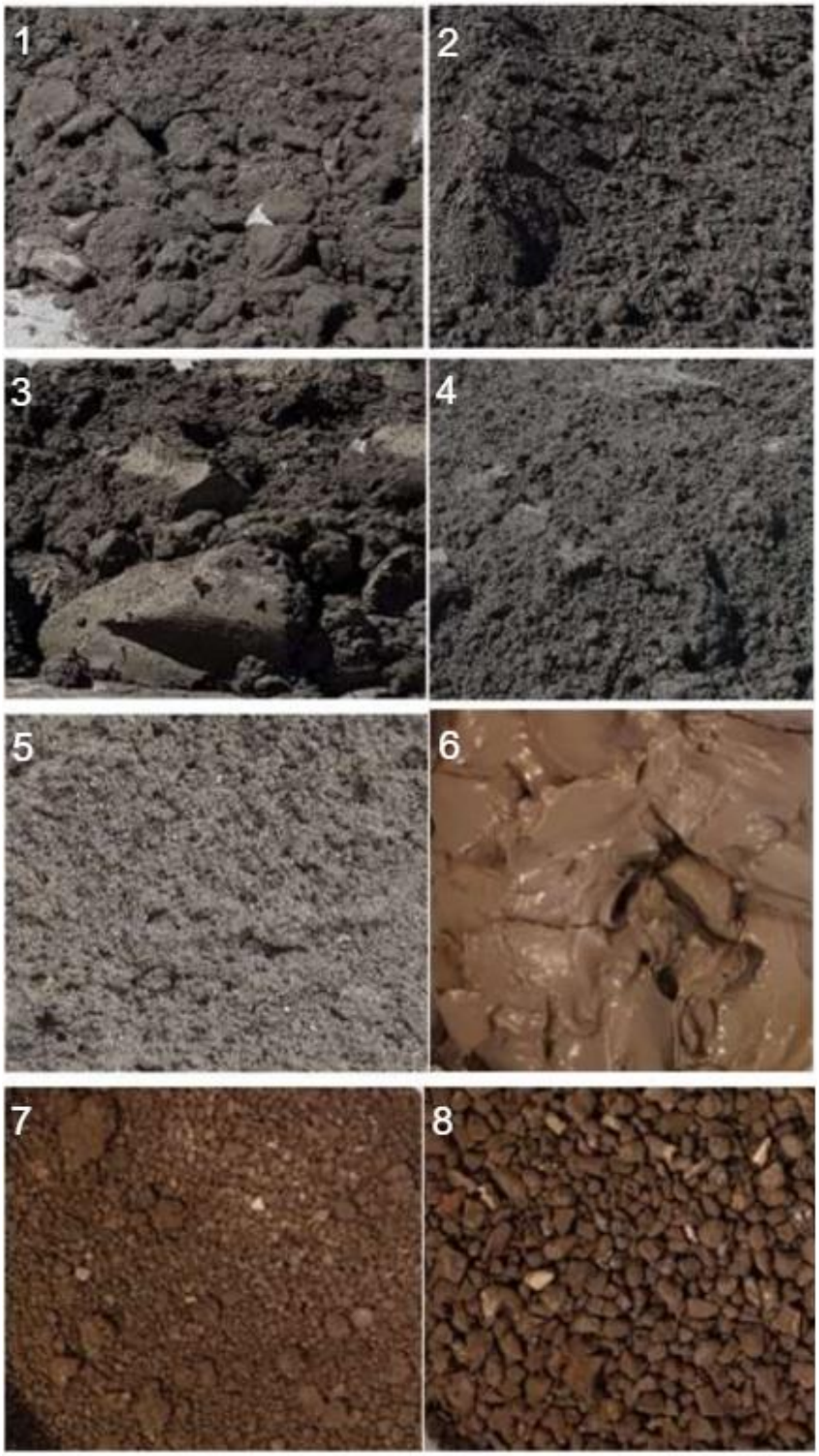


Figure 8.3 MSWI BA -clay mixtures (samples 1-5), clay(sample 6), MSWI BA 0-5mm (sample 7), MSWI BA 5-12.5mm (sample 8)

Laboratory tests for water content, water permeability, grain size distribution, undrained shear strength, optimum moisture content, maximum dry density and pH were done in the geotechnical laboratory of Aalto University. Geotechnical tests were carried out according to Finnish handbook SFS 179-2. pH of samples was measured with pH meter. Specific gravity of the clay sample was determined in the laboratory test and measured 2.76 g/cm^3.

Grain size distribution of the clay sample was figured out using hydrometer test. According to the measurements, there was no organic content in the clay sample or it was below the detection limit. Table 8.3 represents the tests done for determining the pH, water content, undrained shear strength, optimum moisture content, maximum dry density of the samples and the corresponding test results. Pictures of laboratory instruments used for tests are included in the Appendix 10.

Table 8.3 pH, water content and shear strength of the samples

Sample no.	Sample (Test method)	pH	water content %	Undrained shear strength Cu kPa	Optimum moisture content w %	Maximum dry density kg/m³
	Test method	pH meter	Oven dry method	Fall cone test	Standard proctor test	
1	60% clay dry + 40% Bottom Ash (0-5mm)	10·34	33.3	135.7	21.8	1585
2	40% clay dry +60% Bottom Ash (0-5mm)	10·73	25.5	over 245	25.5	1510
3	60% clay wet +40% Bottom Ash (0-5mm)	10·41	37	41.5		
4	40% clay wet +60% Bottom Ash (0-5mm)	10·61	31.2	87.3		
5	40% clay wet +60% Bottom Ash (5-12.5mm)	10·42	21.1	91.2	15.5	1690
6	clay	7·77	48.1	7.81(undisturbed) 1.82(disturbed)		
7	Bottom Ash (0-5mm)	11·07	17.1			
8	Bottom Ash (5-12.5mm)	10·97	9			

As described in Table 8.3, pH level of all MSWI BA-clay mixtures and bottom ash samples are above 10. And there is no considerable difference in the pH value between MSWI BA-clay mixture and bottom ash samples. Water content of the mixtures 1-5 is in between 21.1% - 37%. Undrained shear strength of the mixtures varied between 41.5kPa – over 245 kPa.

Table 8.4 presents the coefficient of water permeability and the dry density of the samples used in the water permeability test. Testing methods also included in the tables. Test results of optimum moisture content and grain size distribution are included in Appendix 11.

Table 8.4 water permeability test results of samples 1-8

	sample	Coefficient of water permeability k	Testing method	dry density of the sample used for water permeability test kg/m³	Degree of compaction
1	60% clay dry + 40% Bottom Ash (0-5mm)	4.82 x 10^{-9} m/s	Falling head method	1375.5	86.8%
2	40% clay dry +60% Bottom Ash (0-5mm)	1.29 x 10^{-8} m/s	Falling head method	1438.4	95.3%
3	60% clay wet +40% Bottom Ash (0-5mm)	4.05 x 10^{-8} m/s	Falling head method	1360.7	
4	40% clay wet +60% Bottom Ash (0-5mm)	2.04 x 10^{-8} m/s	Falling head method	1453.9	
5	40% clay wet +60% Bottom Ash (5-12.5mm)	1.88 x 10^{-8} m/s	Falling head method	1610.9	95.3%
6	clay - sample a	1.29 x 10^{-9} m/s	Oedometer	1148	
	clay - sample b	2.19 x 10^{-9} m/s	Oedometer	1160.8	
7	Bottom Ash (0-5mm)	2.93 x 10^{-4} m/s	Falling head method	893	
8	Bottom Ash (5-12.5mm)	2.75 x 10^{-4} m/s	Falling head method	1186.8	

Coefficient of water permeability for the mixtures 2-5 was in between 1.29 - 4.05x10^{-8}m/s, which is slightly above the recommended value for a temporary landfill cover structure. However, the coefficient of water permeability for sample 1 is determined as 4.82x10^{-9}m/s, which is lower than the recommended value.

8.2 2018-Temporary test cover structure

This temporary cover structure was being constructed during Autumn 2018 (while the thesis writing of this research study was in progress). This structure was situated in a sloped area, in S1 area of Ämmässuo landfill. Figure 8.4 shows the location of this construction in the Ämmässuo landfill.

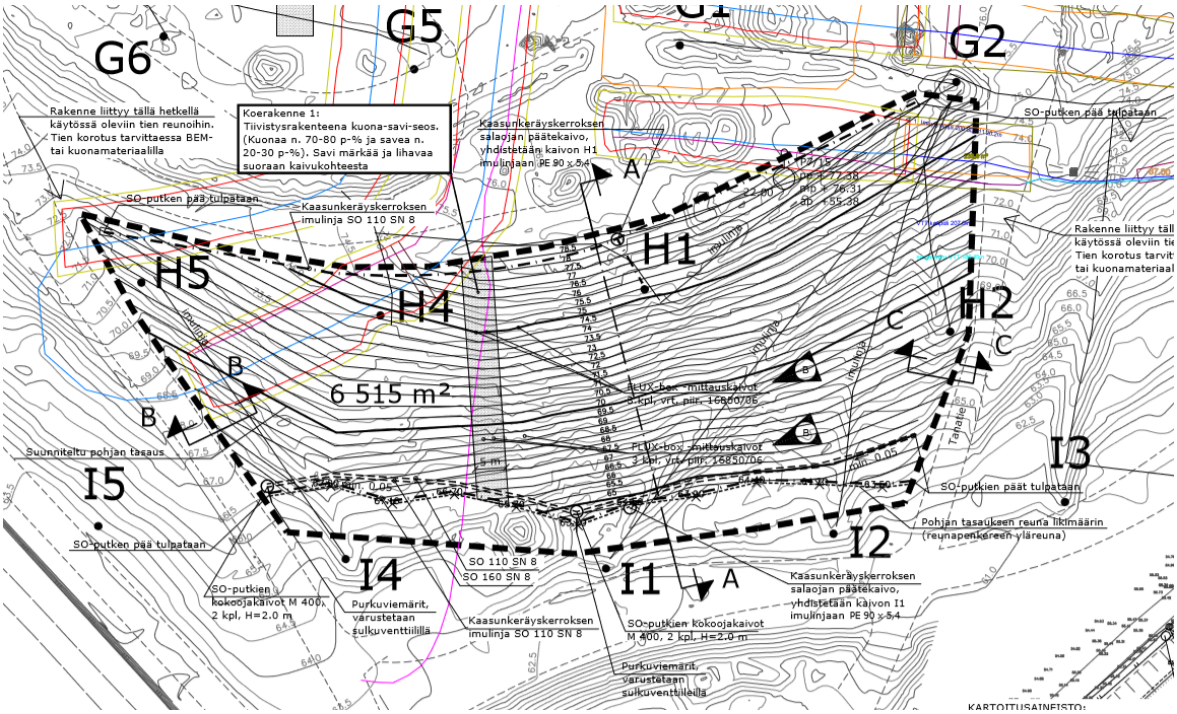


Figure 8.4 Location of 2018 structure (Ramboll, 2018b)

This temporary cover structure includes two different types of structural layers. Bentonite mat was used as impermeable layer in the major part of this cover structure. Another type of structure was done in a 5m wide strip in the slope (shown in the figure 8.4). In that part, instead of bentonite mat, the impermeable layer was constructed with MSWI BA-clay mixture. The mixture used in that structure contained 70% MSWI BA and 30% clay. The design thickness of the layer was 500mm. Figure 8.5 represents the sectional drawing of the test structure.

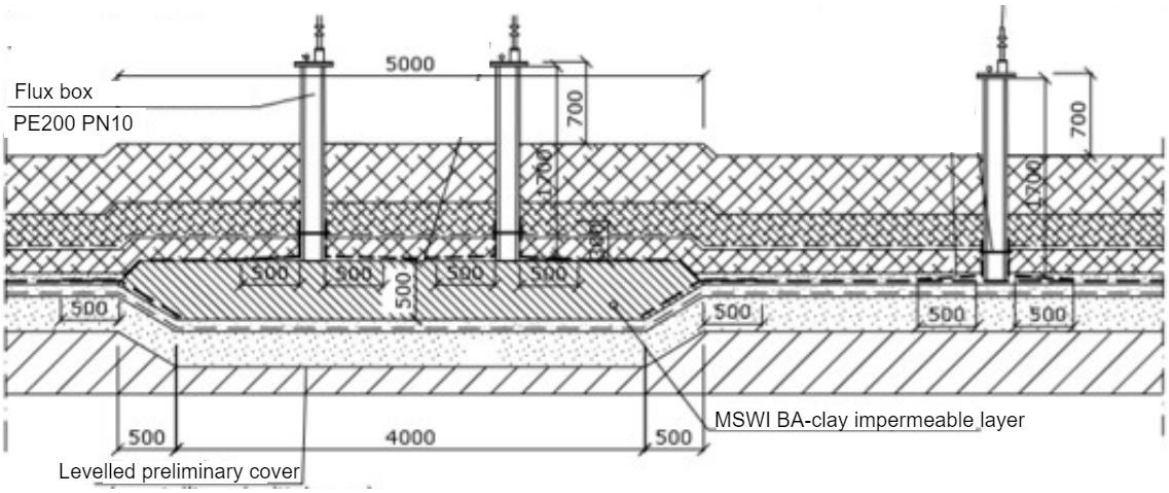


Figure 8.5 cross section 2018 cover structure with MSWI BA -clay mixture (Figure: Ramboll, 2018c)

Flux boxes were included in this structure for assessing the gas emission from the structures. One set of flux boxes were installed above the MSWI BA-clay mixture layer in the 5m strip

region and another one was installed above the bentonite mat. MSWI BA-clay mixture was selected based on the preliminary MSWI BA-clay mixing studies done in this research study. Outcome from the MSWI BA-clay mixing process and test results from this research study has been utilized for understanding the constructability and suitability of the MSWI BA-clay mixture in using as an impermeable layer in the 2018 temporary test cover structure.

Figure 8.6 Test cover structure-2018 during construction

9 Conclusion

Objective of this thesis was to study the gas permeability performance of the landfill cover structures made with MSWI BA. According to the literature review and gas measurements from the two landfill test cover structures, following conclusions can be made.

MSWI BA can be used as a construction material for the landfill cover structures. However, additives had to be incorporated with MSWI BA to ensure the gas permeability of the cover structure. Only a low concentration (close to zero ppm) of landfill gas was measured above the impermeable layer of the cover structure made with 0-2mm MSWI BA (2015 test structure) when 3% polymer modified sodium bentonite was used as an additive. On the other hand, for the landfill test cover structure made with 0-5mm MSWI BA alone (2017 test structure), high concentration of landfill gas was measured above the impermeable layer. And thus, it is evident that the MSWI BA with a proper kind of additives is a very good solution for constructing a landfill cover structure with low gas permeability.

Study results are also in line with the literature that the materials with low coefficient of water permeability are having low gas permeability. The cover structure made with 0-2mm MSWI BA and 3% polymer modified sodium bentonite mixture exhibited required low water permeability and was very effective in reducing the gas emission than the other cover structure. The other cover structure was made with 0-5mm MSWI BA, which had a higher coefficient of water permeability, and was not effective in reducing the gas emission. Quintessentially, it can be also concluded that the impermeable layer with required low water permeability is effective in reducing the landfill gas emission. Thus, coefficient of water permeability can be taken as a scale for low gas permeability while selecting the material for landfill cover structure.

From the experimental study on MSWI BA-clay mixture, it is evident that, coefficient of water permeability in most of the MSWI BA-clay mixtures are higher than the recommended value. Only the mixture 1 with 60% clay of low moisture content exhibited the recommended water permeability. Further studies are required for improving the MSWI BA-clay mixtures to achieve sufficiently low enough water permeability and thereby lower gas permeability.

Concluding, outcome from the MSWI BA-clay mixing process and the test results from this research study has been utilized for understanding the water permeability, constructability and suitability of the MSWI BA-clay mixture in using as an impermeable layer in the Ämmässuo 2018 temporary test landfill cover structure.

10 Recommendations to improve measurements and required future studies

For assessing the efficiency of landfill cover structure, gas emission rate could be measured from the landfill cover surface. This can be done by static chamber (flux box) method, which is explained in the Section 2.4. Measured methane emission rate can be compared with the methane emission rate limit set by other countries. Since gas pressure is a highly influencing the amount of the gas emission through soil layer, pressure sensors can be installed below the impermeable layer to study the gas pressure in the cover structure for future references.

Since the landfill gas emission rate decreases with the increase in impermeable layer thickness, appropriate/optimum thickness of the impermeable layer made with MSWI BA must be determined. This can be done by laboratory tests. However, a thorough study is required in this area.

It is evident from the study that polymer modified sodium bentonite can reduce the water permeability of the MSWI BA – clay mixture. However, polymer modified sodium bentonite is comparatively expensive. Thus, as an economical solution, for decreasing the water permeability of MSWI BA – clay mixture, instead of using polymer modified sodium bentonite as an additive, cheaper type of common bentonites such as sodium bentonite could be tested. However, this kind of bentonites may swell sufficiently, only when the pH is close to 7 (this is still to be verified). Presumably, pH level of 7 can be achieved when the clay with low pH is mixed with the MSWI BA in an appropriate ratio. A detail study is required for verifying this potential economical option.

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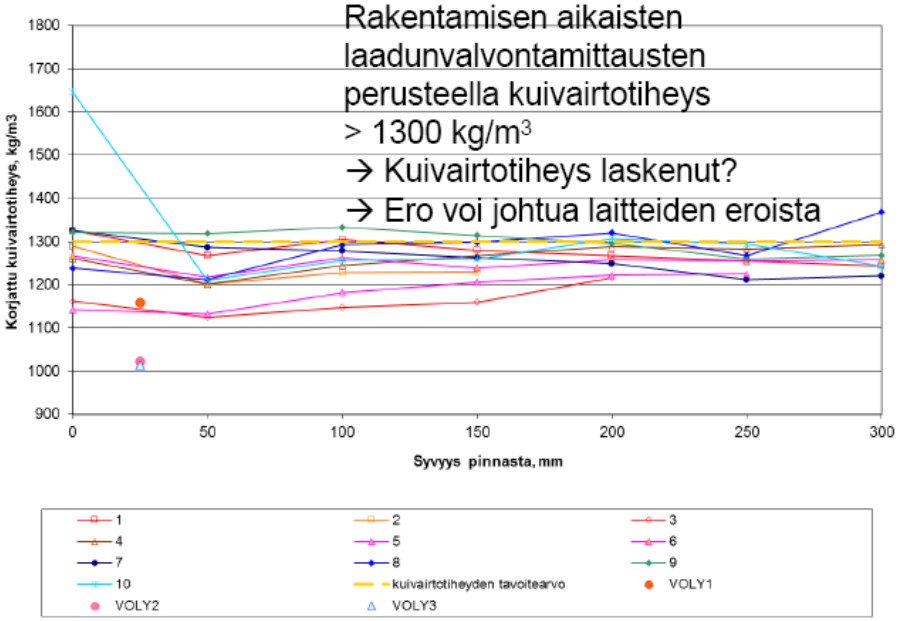
List of appendixes

Table 3. Permeability test results of MIBA fraction 0…2 mm and bentonite mixtures.

Sample	Permeant liquid	Dry density after the test ρ_{dry} (kg/m^3)	Permeability coefficient k (m/s)
#0-2mm	distilled water	1339	1,1E-06
#0-2 mm + CPA 3%	distilled water	1345	6,3E-08
#0-2 mm + CPA 5%	distilled water	1343	2,9E-08
#0-2 mm + CPA+P 3%	distilled water	1341	1,1E-10
#0-2 mm + CPA+P 5%	distilled water	1333	3,9E-10
#0-2 mm	eluate	1351	4,4E-08
#0-2 mm + CPA 3%	eluate	1335	4,7E-08
#0-2 mm + CPA+P 3%	eluate	1353	1,7E-09
#0-2 mm + CPA+P 5%	eluate	1342	7,8E-10
1:1 #0-2 mm + #2-5 mm + CPA 3%	distilled water	1424	4,0E-08
1:1 #0-2 mm + #2-5 mm + CPA+P 3 %	eluate	1455	2,1E-09
1:1 #0-2 mm + #2-5 mm + CPA+P 3 %	eluate	1364	5,0E-08

Kuivairtotiheys korjatun vesipitoisuuden perusteella

Rakentamisen aikaisten laadunvalvontamittausten perusteella kuivairtotiheys
> 1300 kg/m^3
→ Kuivairtotiheys laskenut?
→ Ero voi johtua laitteiden eroista



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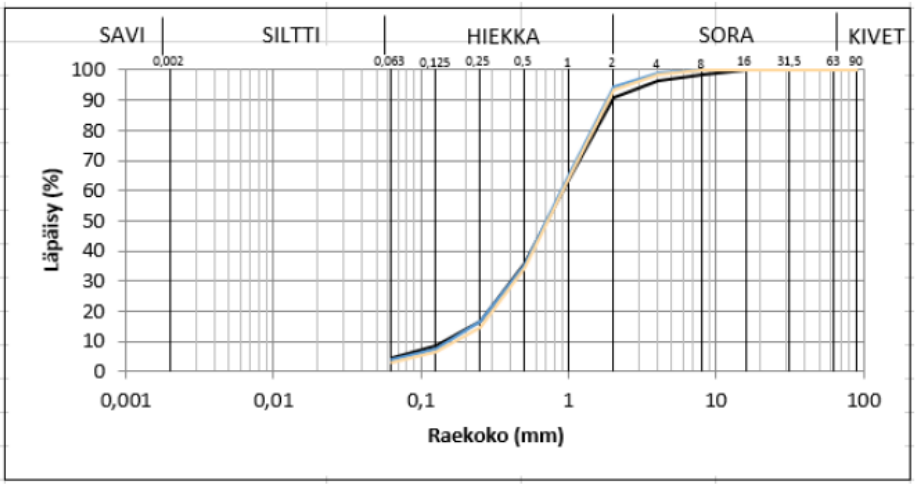
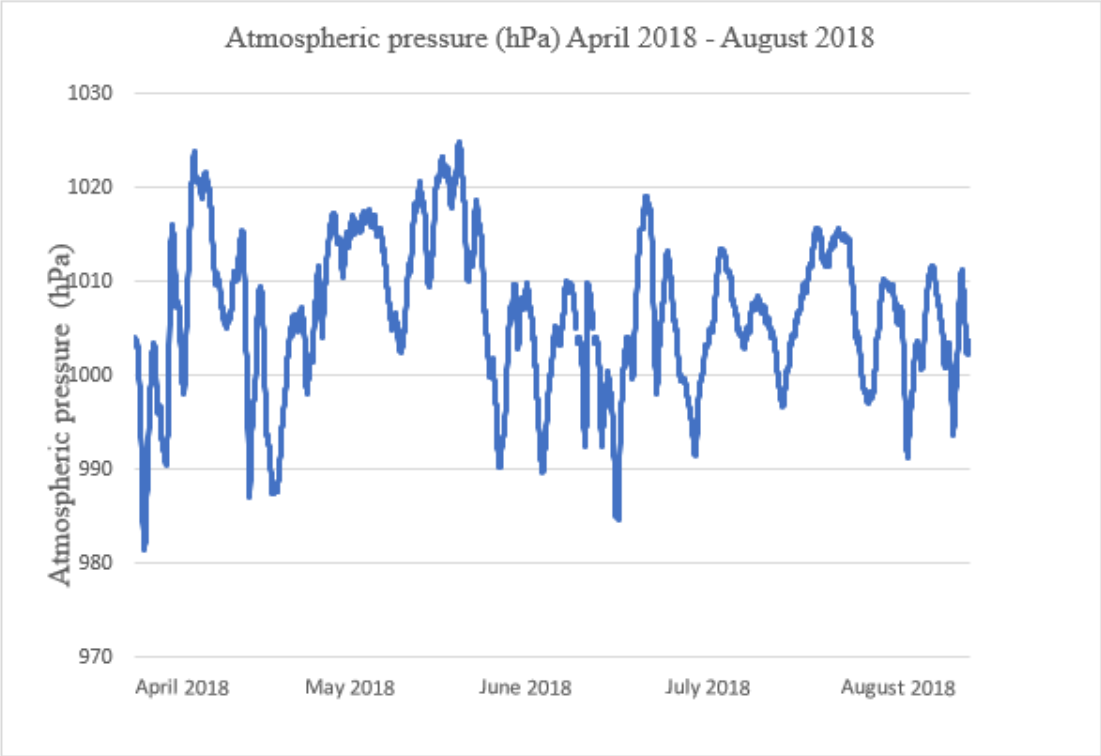
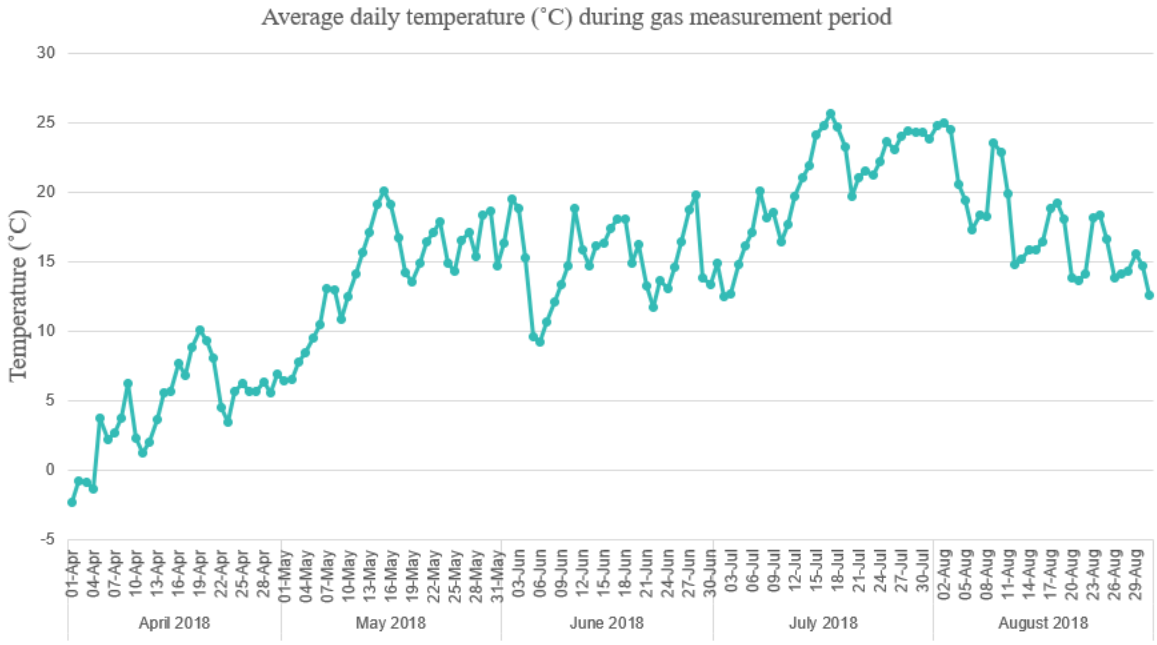
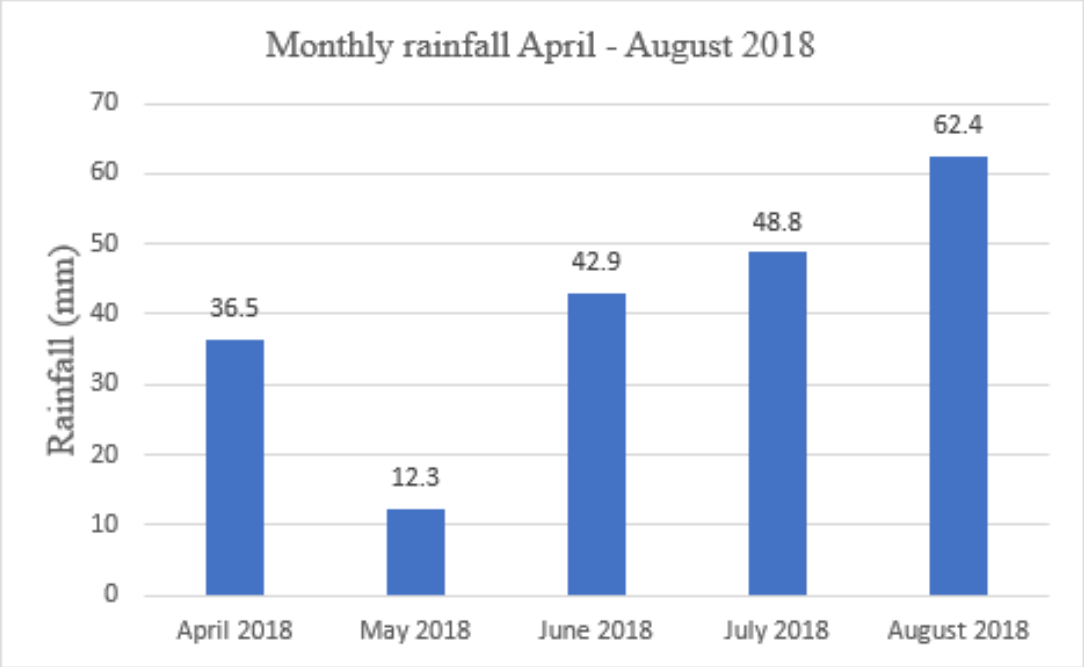


Kuivaseulonta, 3 kpl
ei merkittävää eroa ennakkokokeissa tutkitun #0…2 mm rakeisuuteen


Atmospheric pressure (hPa) April 2018 - August 2018
Atmospheric pressure (hPa)
1030
1020
1010
1000
990
980
970
April 2018
May 2018
June 2018
July 2018
August 2018


Average daily temperature (°C) during gas measurement period
Temperature (°C)
30
25
20
15
10
5
0
-5
01-Apr
04-Apr
07-Apr
10-Apr
13-Apr
16-Apr
19-Apr
22-Apr
25-Apr
28-Apr
01-May
04-May
07-May
10-May
13-May
16-May
19-May
22-May
25-May
28-May
31-May
03-Jun
06-Jun
09-Jun
12-Jun
15-Jun
18-Jun
21-Jun
24-Jun
27-Jun
30-Jun
03-Jul
06-Jul
09-Jul
12-Jul
15-Jul
18-Jul
21-Jul
24-Jul
27-Jul
30-Jul
02-Aug
05-Aug
08-Aug
11-Aug
14-Aug
17-Aug
20-Aug
23-Aug
26-Aug
29-Aug
April 2018
May 2018
June 2018
July 2018
August 2018


Monthly rainfall April - August 2018
Rainfall (mm)
70
60
50
40
30
20
10
0
36.5
12.3
42.9
48.8
62.4
April 2018
May 2018
June 2018
July 2018
August 2018

DATE	ID	CH4	CO 2	O2	H2 S	Balance	BARO PRES S	comments
		%	%	%	ppm	%	mb	
19/04/2018	Flux box 1	0.9	0.6	21.5	7	77.0	1011	
	Flux box 2	0.5	0.2	22.7	0	76.6	1012	
	Flux box 3	1.5	12.4	11.6	0	74.5	1012	
04/05/2018	Flux box 1	0.8	0.4	22.6	0	76.2	1009	
	Flux box 2	0.7	0.3	22.8	0	76.2	1009	
	Flux box 3	1.0	11.3	12.0	0	75.7	1009	
24/05/2018	Flux box 1	0.2	0.1	21.6	2	78.1	1021	
	Flux box 2	0.8	0.1	21.5	0	77.6	1022	
	Flux box 3	1.6	16.2	5.0	0	77.2	1021	
31/05/2018	Flux box 1	0.0	0.2	18.9	0	80.9	1015	
	Flux box 2	1.0	0.2	19.1	0	79.7	1015	
	Flux box 3	0.3	15.7	4.8	0	79.2	1015	
07/06/2018	Flux box 1	0.7	0.3	22.4	0	76.6	1009	
	Flux box 2	1.2	0.2	22.6	0	76.0	1009	
	Flux box 3	0.5	9.0	13.7	0	76.8	1009	
20/06/2018	Flux box 1	0.5	0.5	19.0	0	80.0	997	
	Flux box 2	0.3	0.4	19.0	0	80.3	997	
	Flux box 3	0.0	5.3	10.8	0	83.9	998	
13/07/2018	Flux box 1	0.5	0.3	20.4	1	78.8	1007	
	Flux box 2	0.4	0.3	20.6	1	78.7	1007	
	Flux box 3	0.3	17.2	3.5	1	79.0	1007	
20/07/2018	Flux box 1	0.1	0.3	19.5	0	80.1	999	
	Flux box 2	0.2	0.2	19.6	0	80.0	999	
	Flux box 3	0.2	19.3	2.7	0	77.8	999	
27/07/2018	Flux box 1	0	0.2	0	0	99.8	1013	seems error in the measured oxygen content.
	Flux box 2	0.4	0.2	18.1	0	81.3	1013	
	Flux box 3	0.2	19.6	0	0	80.2	1027	
31/07/2018	Flux box 1	0.3	0.3	20.3	1	79.1	1015	
	Flux box 2	0.1	0.3	20.4	0	79.2	1015	
	Flux box 3	0.2	19.0	2.1	0	78.7	1015	
06/08/2018	Flux box 1	0.5	0.5	Not availabl e	0	Not availabl e	996	Gas analyser could not measure oxygen content
	Flux box 2	0.2	0.3		0		996	
	Flux box 3	0.1	17.1		0		996	

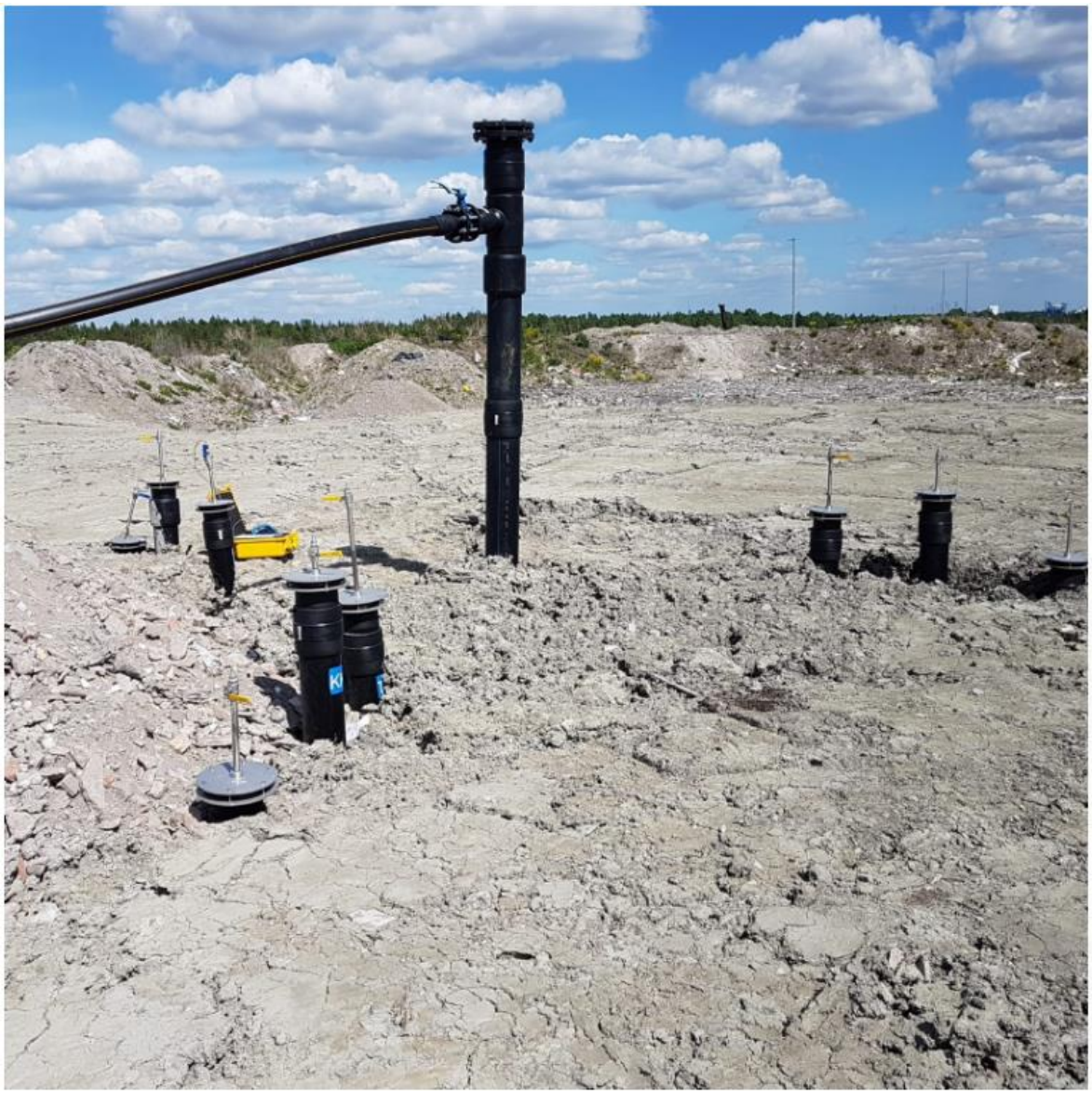
Flow from well D8 (m3/h)	DATE	ID	CH4	CO2	H2S	O2	Balance	BARO PRESS	Comments
			%	%	ppm	%	%	mb	
0.1 m3/h	12/04/2018	1 KK	43.1	32.0	5	0.3	24.6	1020	
		1 TKA	36.4	26.4	2	1.0	36.2	1019	
		1 TKY	0.4	0.1	1	22.2	77.3	1019	
		2 KK	9.3	15.8	6	5.6	69.3	1020	
		2 TKA	33.2	23.0	16	7.8	36.0	1020	
		2 TKY	26.1	17.6	11	10.7	45.6	1020	
		3 KK	64.6	38.7	3	0.3	-3.6	1020	
		3 TKA	21.2	17.6	3	9.8	51.4	1020	
		3 TKY	8.1	4.1	3	18.9	68.9	1019	
		4 KK	34.1	31.2	2	0.7	34.0	1020	
		4 TKA	25.0	23.0	0	3.9	48.1	1020	
		4 TKY	2.0	1.9	0	21.5	74.6	1020	
		D8	13.0	9.4	0	17.1	60.5	1019	
0.0 m3/h	16/04/2018	1 KK	0.4	0.1	0	21.8	77.7	1004	
		1 TKA	23.9	14.5	0	11.0	50.6	1006	
		1 TKY	7.6	5.5	0	18.2	68.7	1007	
		2 KK	11.6	10.7	0	17.8	59.9	1006	
		2 TKA	5.2	8.3	0	13.8	72.7	1006	
		2 TKY	44.7	31.6	0	1.3	22.4	1006	
		3 KK	8.6	5.1	0	19.3	67.0	1006	
		3 TKA	27.3	15.6	0	13.6	43.5	1006	
		3 TKY	46.6	35.1	1	3.0	15.3	1006	
		4 KK	20.3	10.2	0	10.2	59.3	1006	
		4 TKA	12.4	11.7	0	13.9	62.0	1006	
		4 TKY	42.8	30.3	0	3.0	23.9	1006	
		D8	35.1	26.0	0	2.6	36.3	1006	
0.0 m3/h	19/04/2018	1 KK	0.4	0.1	0	22.1	77.4	1012	
		1 TKA	32.0	27.9	0	5.3	34.8	1012	
		1 TKY	0.4	0.1	0	21.8	77.7	1011	
		2KK	0.4	0.4	0	22.8	76.4	1011	
		2 TKA	27.0	25.3	0	10.3	37.4	1011	
		2 TKY	11.0	7.8	0	17.4	63.8	1012	
		3 KK	24.6	19.4	0	10.5	45.5	1012	
		3 TKA	45.8	33.5	0	0.9	19.8	1012	
		3 TKY	31.5	25.3	0	4.1	39.1	1012	
		4 KK	50.6	37.7	0	0.0	11.7	1011	
		4 TKA	39.4	31.0	0	2.6	27.0	1012	
		4 TKY	13.9	9.9	0	15.8	60.4	1011	
		D8	61.9	41.3	1	0.5	-3.7	1012	

Flow from well D8 (m3/h)	DATE	ID	CH4	CO2	H2S	O2	Balance	BARO PRESS	Comments
			%	%	ppm	%	%	mb	
Not available	04/05/2018	1 KK	0.6	5.0	0	16.8	77.6	1008	Valve was opened few days before measurement. Could not measure flow.
		1 TKA	55.3	40.5	0	1.1	3.1	1008	
		1 TKY	0.4	0.1	0	21.7	77.8	1007	
		2KK	0.4	0.2	0	22.3	77.1	1008	
		2 TKA	8.0	1.7	0	20.2	70.1	1008	
		2 TKY	4.5	0.4	0	21.0	74.1	1007	
		3 KK	1.1	4.0	0	19.8	75.1	1008	
		3 TKA	23.6	2.5	0	15.7	58.2	1008	
		3 TKY	3.7	0.2	0	21.3	74.8	1009	
		4 KK	10.6	21.9	0	0.1	67.4	1008	
		4 TKA	30.7	15.5	0	10.8	43.0	1008	
		4 TKY	0.4	0.1	0	22.5	77.0	1008	
		D8	30.7	25.6	0	3.5	40.2	1010	
6.4m3/h	24/05/2018	1 KK	0.6	18.3	0	0.3	80.8	1021	
		1 TKA	33.3	29.1	1	5.0	32.6	1021	
		1 TKY	0.3	0.1	0	20.3	79.3	1019	
		2KK	0.2	0.1	0	20.7	79.0	1021	
		2 TKA	2.5	3.6	1	18.6	75.3	1021	
		2 TKY	0.3	0.6	0	19.8	79.3	1021	
		3 KK	0.4	2.8	0	16.8	80.0	1021	
		3 TKA	0.4	1.3	2	20.5	77.8	1021	
		3 TKY	0.3	0.3	0	20.9	78.5	1021	
		4 KK	7.6	20.4	2	0.2	71.8	1021	
		4 TKA	0.4	2.2	1	19.8	77.6	1021	
		4 TKY	0.3	0.1	0	21.5	78.1	1021	
		D8	34.3	28.1	4	4.1	33.5	1022	
3.2m3/h	31/05/2018	1 KK	0.3	16.2	0	1.0	82.5	1014	
		1 TKA	28.0	26.6	0	5.3	40.1	1014	
		1 TKY	0.1	0.2	0	19.7	80.0	1014	
		2KK	0.8	2.9	0	17.5	78.8	1014	
		2 TKA	1.0	3.2	0	17.8	78.0	1014	
		2 TKY	0.1	0.8	0	18.7	80.4	1014	
		3 KK	0.1	3.8	0	15.0	81.1	1014	
		3 TKA	0.7	2.3	0	18.1	78.9	1014	
		3 TKY	0.1	0.4	0	19.3	80.2	1008	
		4 KK	5.5	22.1	0	0.1	72.3	1014	
		4 TKA	0.7	3.8	0	17.0	78.5	1015	
		4 TKY	0.0	0.2	0	19.2	80.6	1014	
		D8	26.0	24.8	8	4.5	44.7	1016	

Flow from well D8 (m3/h)	DATE	ID	CH4	CO2	H2S	O2	Balance	BARO PRESS	Comments
			%	%	ppm	%	%	mb	
5.5m3/h	07/06/2018	1 KK	0.6	17.3	0	0.0	82.1	1009	
		1 TKA	44.6	35.3	0	2.3	17.8	1008	
		1 TKY	0.5	0.1	0	22.1	77.3	1008	
		2KK	0.5	0.1	0	22.3	77.1	1008	
		2 TKA	2.2	1.9	0	20.8	75.1	1008	
		2 TKY	0.5	0.4	0	21.8	77.3	1008	
		3 KK	0.5	3.4	0	19.1	77.0	1008	
		3 TKA	0.9	1.0	0	21.5	76.6	1008	
		3 TKY	0.5	0.2	0	22.3	77.0	1008	
		4 KK	7.2	22.7	0	0.3	69.8	1008	
		4 TKA	1.1	2.1	0	20.1	76.7	1008	
		4 TKY	0.4	0.1	0	22.5	77.0	1008	
		D8	33.5	27.9	183	4.3	34.3	1009	
6.8m3/h	20/06/2018	1 KK	7.8	19.5	0	3.1	69.6	996	
		1 TKA	21.7	21.5	0	4.6	52.2	996	
		1 TKY	0.1	0.3	0	19.3	80.3	996	
		2KK	0.1	0.2	0	19.3	80.4	996	
		2 TKA	0.4	2.5	0	18.0	79.1	996	
		2 TKY	0.1	0.4	0	19.1	80.4	996	
		3 KK	24.1	20.6	0	6.4	48.9	996	
		3 TKA	15.4	11.7	0	12.4	60.5	997	
		3 TKY	0.3	0.5	0	18.9	80.3	997	
		4 KK	20.1	29.7	0	0.1	50.1	997	
		4 TKA	15.9	17.5	0	8.6	58.0	997	
		4 TKY	0.2	0.5	0	19.0	80.3	997	
		D8	29.5	30.6	34	4.2	35.7	997	
6m3/h	13/07/2018	1 KK	0.4	12.8	0	2.1	84.7	1006	
		1 TKA	16.7	22.7	1	1.2	59.4	1006	
		1 TKY	0.4	0.1	0	20.9	78.6	1006	
		2KK	0.4	3.2	1	15.6	80.8	1006	
		2 TKA	1.4	1.8	1	16.8	80.0	1006	
		2 TKY	0.5	0.4	1	19.5	79.6	1006	
		3 KK	0.4	3.0	0	16.0	80.6	1006	
		3 TKA	1.3	1.3	1	17.7	79.7	1006	
		3 TKY	0.4	0.3	0	20.1	79.2	1006	
		4 KK	7.1	20.3	1	0.4	72.2	1006	
		4 TKA	0.8	3.4	2	14.2	81.6	1006	
		4 TKY	0.3	0.2	0	20.0	79.5	1006	
		D8	37.6	29.8	159	3.1	29.5	1010	

Flow from well D8 (m3/h)	DATE	ID	CH4	CO2	H2S	O2	Balance	BARO PRESS	Comments
			%	%	ppm	%	%	mb	
5.7m3/h	20/07/2018	1 KK	0.1	12.2	0	2.7	85.0	998	
		1 TKA	15.2	20.9	0	2.2	61.7	997	
		1 TKY	0	0.2	0	18.8	81.0	999	
		2KK	0	0.1	0	19.2	80.7	999	
		2 TKA	0.2	2	0	17	80.8	999	
		2 TKY	0	0.4	0	18.5	81.1	998	
		3 KK	0	3.1	0	14.8	82.1	999	
		3 TKA	0.2	1.2	0	18	80.6	999	
		3 TKY	0	0.3	0	19.2	80.5	998	
		4 KK	5.9	20.6	0	0.5	73.0	999	
		4 TKA	0.3	3.3	0	15.6	80.8	999	
		4 TKY	0	0.2	0	19.4	80.4	999	
		D8	33.4	28.9	37	3.2	34.5	999	
0.0 m3/h	27/07/2018	1 KK	0.8	11.9	0	1.1	86.2	1011	Closed flow just before the measurement
		1 TKA	16.6	22	0	0.1	61.3	1011	
		1 TKY	0	0.4	0	18.3	81.3	1011	
		2KK	0	2.6	0	15.3	82.1	1012	
		2 TKA	1	5	0	13.5	80.5	1011	
		2 TKY	0.1	0.5	0	17.9	81.5	1012	
		3 KK	0	3.2	0	13.2	83.6	1012	
		3 TKA	0.4	2.6	0	15.9	81.1	1012	
		3 TKY	0	0.5	0	17.6	81.9	1012	
		4 KK	15	22.5	0	0.4	62.1	1012	
		4 TKA	0.1	3.1	0	14.9	81.9	1012	
		4 TKY	6.1	4.2	0	5.5	84.2	1012	
		D8	31	26.5	164	3.2	39.3	1013	
0.07m3/h	31/07/2018	1 KK	14.0	24.5	2	0.0	61.5	1014	
		1 TKA	36.7	32.7	2	0.3	30.3	1014	
		1 TKY	0.3	0.3	1	20.7	78.7	1014	
		2KK	0.1	0.1	0	20.7	79.1	1014	
		2 TKA	45.5	32.8	1	1.0	20.7	1014	
		2 TKY	22.2	1.8	0	12.5	63.5	1014	
		3 KK	54.2	39.3	0	0.0	6.5	1015	
		3 TKA	45.8	32.7	1	1.5	20.0	1015	
		3 TKY	58.1	29.1	1	0.5	12.3	1014	
		4 KK	42.7	34.7	2	0.0	22.6	1014	
		4 TKA	35.7	30.9	2	0.0	33.4	1015	
		4 TKY	19.8	16.8	2	4.0	59.4	1014	
		D8	53.1	38.5	260	0.6	7.8	1016	

Flow from well D8 (m3/h)	DATE	ID	CH4	CO2	H2S	O2	Balance	BARO PRESS	Comments
			%	%	ppm	%	%	mb	
0.0m3/h	06/08/2018	1 KK	34.5	31.2	0	NA - Analyser couldn't measure oxygen.		995	Amount of oxygen was not available. Gas analyser could not measure oxygen.
		1 TKA	48.1	37.9	0			995	
		1 TKY	0.1	0.2	0			995	
		2KK	0.0	0.2	0			995	
		2 TKA	36.1	31.8	0			995	
		2 TKY	4.6	8.8	0			995	
		3 KK	53.3	40.3	0			995	
		3 TKA	40.2	31.6	0			995	
		3 TKY	7.6	14.7	0			995	
		4 KK	52.6	39.3	0			989	
		4 TKA	46.0	35.2	0			995	
		4 TKY	42.2	29.7	0			995	
		D8	57.6	42.1	619			996	




VOLVO
DX225LC


VOLVO
renta
92472
renta
SD135B


VOLVO
renta
92472
renta
SD135B

27.6.2018 SAVI + KUONA KOESEKOITUS ÄMMÄSSUO 2.7.2018 / mtm

Valmistimme koneasemalla SM 5000 muutaman annoksen savi ja kuonasekoituksia.
Tässä taulukossa koetiivistyksistä tehdyt tiiveysmittaukset Troxlerilla ja hiekkavolymetrillä.

TROXLER- MITTAUKSET

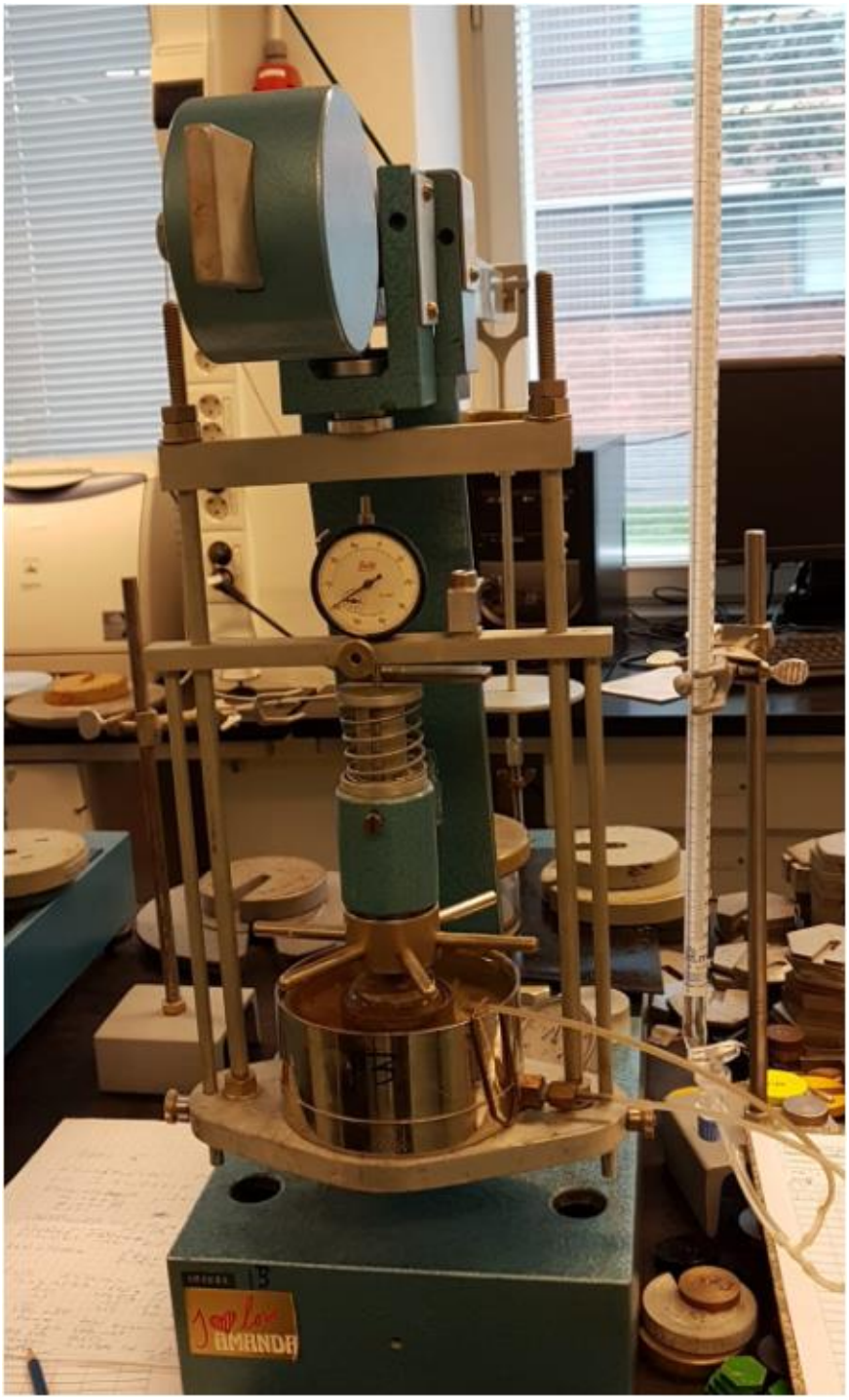
Kuiva savi

1.	Savi 60 %	Kuona 0-5 40 %			2.	Savi 40 %	Kuona 0-5 60 %		
Troxler									
	50 mm	100 mm	150 mm	Hiekkavolymetri		50 mm	100 mm	150 mm	Hiekkavolymetri
DD	1586	1558	1534	1139	DD	1624	1624	1616	1604
WD	1902	1869	1847	1518	WD	1941	1920	1932	2035
W	20,0	20,4	20,4	33,3	W	19,5	18,2	19,5	26,8

Märkä savi

3.	Savi 60 %	Kuona 0-5 40 %			4.	Savi 40 %	Kuona 0-5 60 %		
	50 mm	100 mm	150 mm	Hiekkavolymetri		50 mm	100 mm	150 mm	Hiekkavolymetri
DD	1494	1472	1435	1667	DD	1599	1566	1560	1599
WD	1869	1824	1806	2254	WD	1928	1901	1894	2084
W	25,1	24	25,9	35,2	W	20,6	21,4	21,4	30,3

5.	Savi 40 %	Kuona 5-12 60 %	
	50 mm	100 mm	Hiekkavolymetri
DD	1818	1788	1786
WD	2026	1995	2178
W	11,5	11,6	22,0



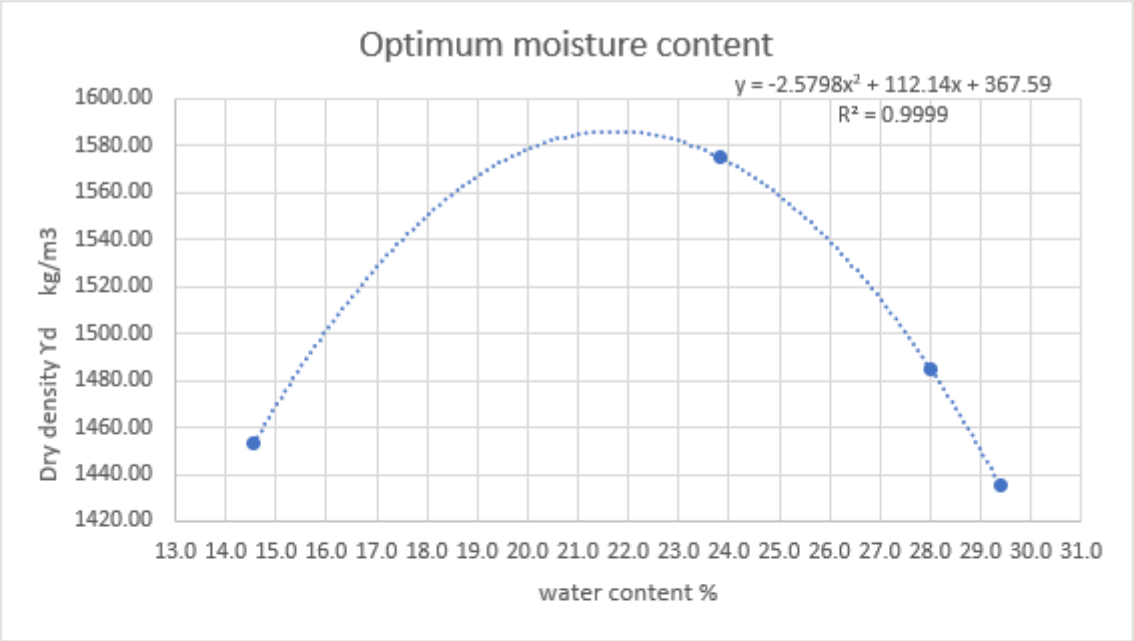


Figure: optimum moisture content graph sample 1. 60% clay dry + 40% BA 0-5mm

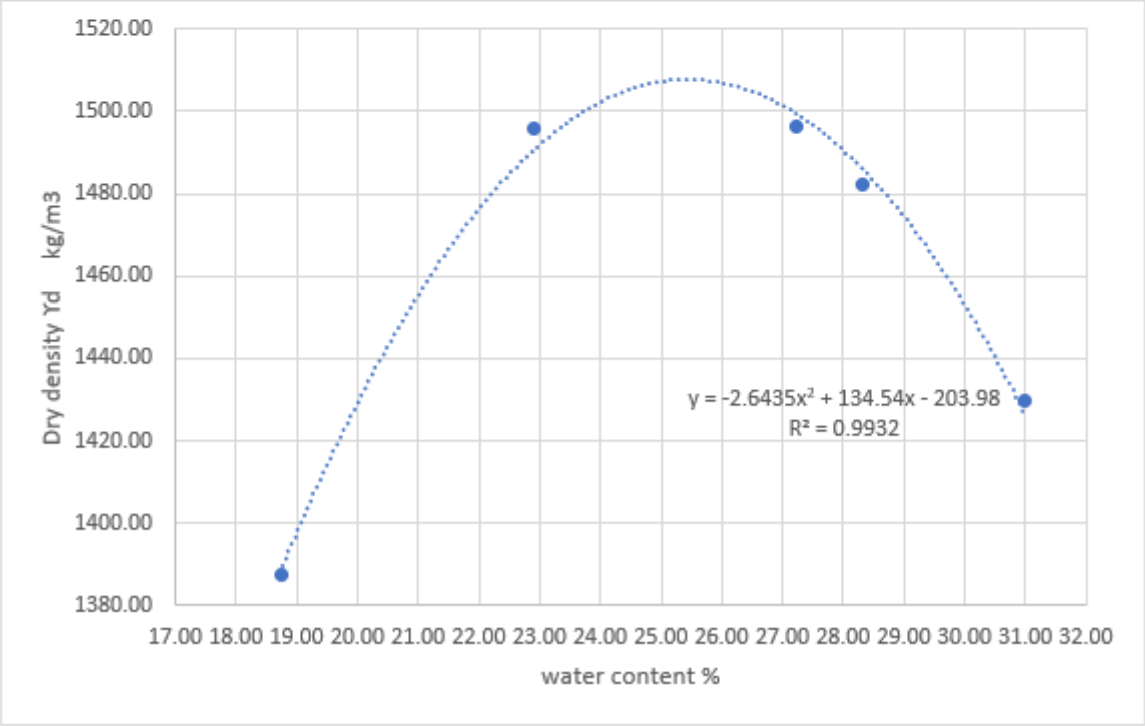


Figure: optimum moisture content graph sample 2. 40% clay dry + 60% BA 0-5mm

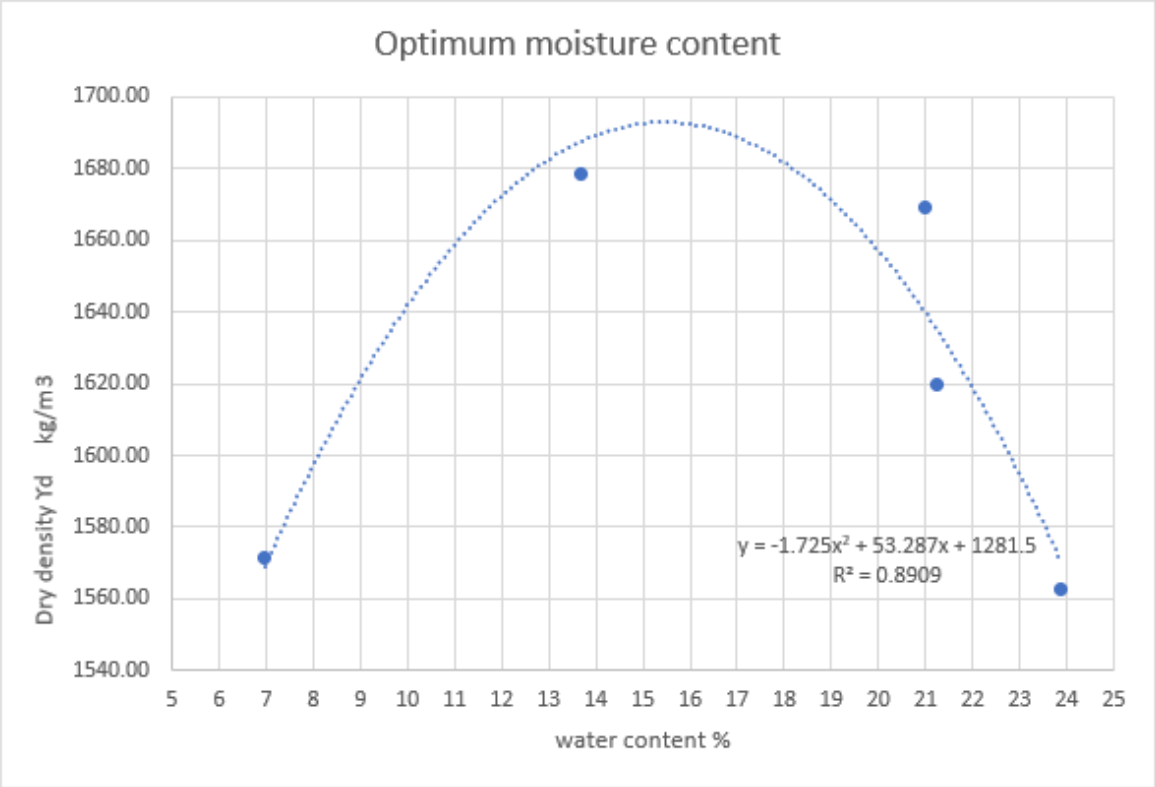
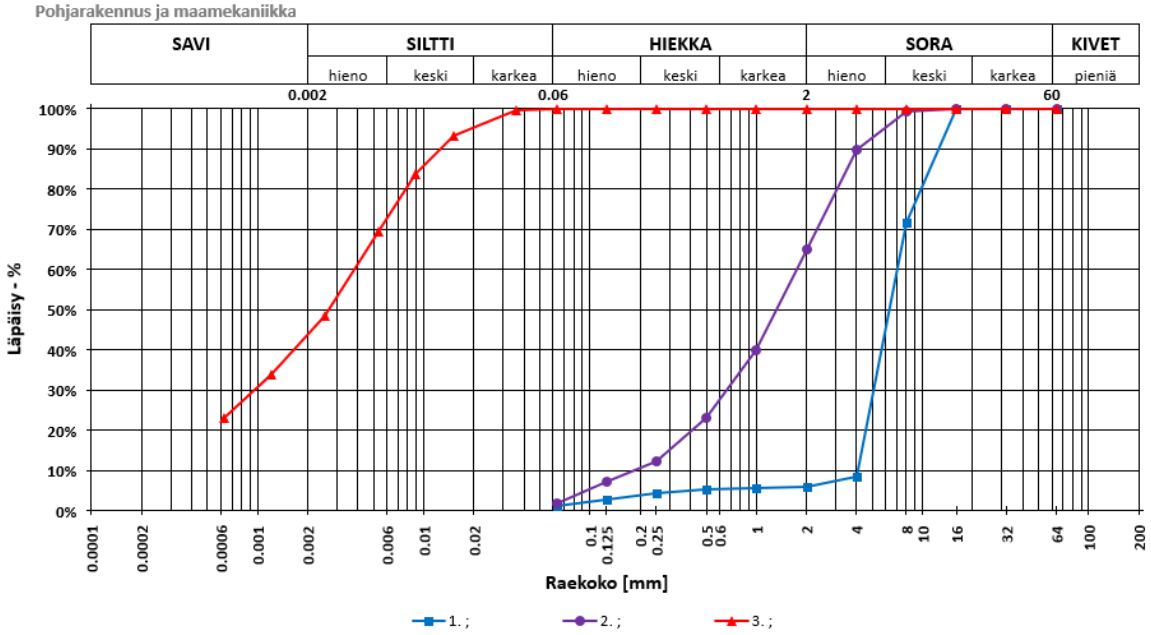


Figure: optimum moisture content graph sample 5. 40% clay wet + 60% BA 5-12.5mm

Aalto-yliopisto
Insinööritieteiden korkeakoulu
Pohjarakennus ja maamekaniikka

GEO-maalajiluokitus



GEO: 1. BA 5-12.5mm 2. BA 0-5mm 3. clay 4. 5. 6.
ISO: 1. Gr 2. grSa 3. Cl 4. 5. 6.